एनटीपीसी
NTPC

SYNCHRONOUS CONDENSER

A NOVEL SOLUTION FOR GRID STABILITY FOR INTEGRATION OF RENEWABLES

(VERSION 2.0)

Solution for
- Short Circuit Power
- Inertia
- Dynamic Reactive Power

"An Old Tool Rediscovered to Address New Grid Challenges"

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Message

As per the updated NDC (Nationally Determined Contributions), India stands committed to reduce emission intensity of its GDP by 45 percent by 2030, from 2005 level, and achieving about 50 percent cumulative electric power installed capacity from non-fossil fuel-based energy sources by 2030. India's installed capacity (as on 31.03.2024) from non-fossil fuel-based capacity is around 198.6 GW which is 45% of the total installed capacity of 441.9 GW. Also, at COP26, the Hon'ble Prime Minister has announced commitment of achieving 500 GW of installed capacity from non-fossil fuel-based sources by 2030.

As a result of the changing generation mix i.e., decrease in conventional synchronous generation coupled with increase in Renewable energy sources such as Solar PV, wind generators etc., dynamic characteristics of the power system such as inertia, short circuit power and dynamic reactive power need to be studied with the planned renewable integration and suitable compensation devices must be installed to ensure grid stability and reliability in all scenarios.

I am happy to note that NTPC Engineering Team has carried out a broad study for identification of some of the challenges for grid stability with the planned RE integration and possible role/modalities of synchronous condenser installations in the changing generation mix. The report prepared by NTPC team can help in identifying the actions which need to be taken by various stakeholders for paving a way for a stable and resilient grid.

I would like to acknowledge the contribution of all team members associated with this project and would also thank all the stakeholders for sharing information and support for preparation of the report.

(K. Shanmugha Sundaram)
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Message

The energy transition is rapidly changing the generation mix in the power system. Global experience in this regard suggests that the displacement of conventional generation sources with inverter-based Renewable energy sources such as Solar PV, wind generators etc., shall have an impact on the power system inertia, short circuit strength and dynamic reactive power. These ancillary services have inherently been provided by the conventional synchronous generators and therefore need for installing separate compensation devices for these ancillary services has never been felt in the pre-renewable era. The renewable generators connected through the power electronic devices pose challenges to the power system as they cannot provide inertia, have the limitations of providing short circuit power and dynamic reactive power in the system. Considering these challenges, dynamic characteristics of the power system need to be studied with the planned RE integration and suitable measures need to be in place to ensure grid stability and reliability considering the future scenario.

Considering the aggressive target of integrating RE capacity in India, NTPC has carried out a broad study which provides details of some of the challenges that may arise in future due to the changing generation mix, possible solutions for addressing these challenges, possibility of using synchronous condenser as one of the solutions, modalities and challenges for re-purposing of retiring assets as synchronous condensers, advantages of new synchronous condenser installations, requirement of uniform regulations and cost recovery models for compensation of such devices. I am sure that the report shall help in identifying the actions for ensuring a stable and resilient grid in the context of the future Indian power system scenario.

I would like to acknowledge and congratulate all the team members associated with this study and would also thank all the stakeholders that have contributed for preparation of this report.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND SYMBOLS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND SYMBOLS

AC	Alternating Current
APC	Auxiliary Power Consumption
AVR	Automatic Voltage Regulator
BESS	Battery Energy Storage System
CEA	Central Electricity Authority
CW	Cooling Water
DC	Direct Current
EHV	Extra High Voltage
E-STATCOM	Enhanced Static Synchronous Compensator
FACTS	Flexible AC Transmission System
GCB	Generator Circuit Breaker
GENCO	Generation Company
GT	Gas Turbine
GTO	Gate Turn-Off Thyristor
GW	Gigawatt
H	Inertia Constant
HVDC	High Voltage Direct Current
Hz	Hertz
IGBT	Insulated Gate Bi-polar Transistor
IPBD	Isolated Phase Bus Duct
KA	Kilo Ampere
KV	Kilo Volt
LA	Lightning Arrester
LV	Low Voltage
MOU	Memorandum of Understanding
MV	Medium Voltage
MVA	Mega Volt Amperes
MVAR	Mega Volt Amps Reactive
MW	Megawatt
NDC	Nationally Determined Contributions
NZE	Net Zero Emission
O&M	Operation and Maintenance
OEM	Original Equipment Manufacturer
PCC	Point of Common Coupling
PLF	Plant Load Factor
PSP	Pumped Storage Plants
PU	Per unit
R&M	Renovation and Modernization

RE	Renewable Energy
RoCoF	Rate of Change of Frequency
ROE	Return on Equity
Rpm	Revolutions per minute
SCP	Short Circuit Power
SCR	Short Circuit Ratio
SFC	Static Frequency Converter
SIR	Synchronous Inertial Response
SLD	Single Line Diagram
STATCOMs	Static Synchronous Compensator
SVC	Static VAR Compensators
TRANSCO	Transmission Company
TSC	Thyristor Switched Capacitors
TSR	Thyristor Switched Reactors
UHVDC	Ultra-High Voltage Direct Current
VFD	Variable Frequency Drive
VSC	Voltage Source Converter
VT	Voltage Transformer
Xd	Direct Axis Synchronous Reactance
Xd’	Direct Axis Transient Reactance
Xq	Quadrature Axis Synchronous Reactance
Xq’	Quadrature Axis Transient Reactance

EXECUTIVE SUMMARY

In order to achieve Green House Emission targets and to reduce dependency on fossil fuel-based generation, most of the countries around the world are planning to increase the generation from renewable sources. As per the updated NDC, India stands committed to achieve 50% cumulative electric power installed capacity from non-fossil fuel-based sources by 2030 and reduce Emission Intensity of its GDP by 45% by 2030, from 2005 level. For achieving the COP26 commitments and Net Zero Emission (NZE) targets, there has been constant addition of renewable energy in the Indian grid over the past few years and now we are approaching a point where we shall start withdrawing conventional energy from the grid.

Power System Inertia, Short Circuit Power and Dynamic Reactive Power, which are the key elements of grid stability have inherently been provided by the conventional generators. The Renewable Energy generators are integrated into the power system with the use of inverter-based power electronic devices. The renewable generators connected through these power electronic devices pose challenges to the power system as they cannot provide inertia, have the limitations of providing short circuit power, reactive power compensation and may also introduce harmonics in the power system. Therefore, the increase in renewable energy sources coupled with the withdrawal of conventional energy-based plants will pose considerable challenges for grid stability in future.

The report brings out the challenging aspects of requirement of short circuit power, inertia and reactive power management in the changing grid scenario. Further, the report deliberates on the future renewable scenario in India, challenges with such high renewable integration and available technologies for dealing with these challenges. The report highlights that synchronous condensers may be one of the most optimized and strongest technical solution to deal with problems of low inertia, short circuit power and requirement of reactive power reserves due to changing grid scenarios. The technical details, components, layout requirements for installation of synchronous condenser have been included in the report. Further, the retiring units' scenario in India, modalities for repurposing of retiring thermal assets as synchronous condenser, technical details for conversions etc. have been discussed in the report. Also, the benefits of new synchronous condensers and challenges for re-purposing the existing coal-based power plants as synchronous condensers are included as a part of the report. The report highlights the importance of a uniform tariff regulation and cost recovery model for all such compensation devices, for installation of the most suitable solution and promoting investment in these areas. Further, details of global synchronous condenser installations are also listed in the report.

A simulation study on IEEE 14 bus system has been carried out in the report to highlight the impact of high penetration of renewables in a network with no conventional generation in nearby vicinity. Short circuit ratio (SCR) at nodes/point of interconnection after integration of RE Generators with and without the use of synchronous condensers are indicated in the case study. Also, a simulation study for dynamic reactive power capability of some of the available technologies have been presented. Further, efforts were carried out to capture frequency response and inertia constant using different compensation devices. However, based on the results obtained, it was concluded that Electromagnetic Transient (EMT) simulation software like PSCAD/EMTP might represent these dynamic characteristics accurately compared to RMS simulation software like PSSE. Therefore, to ensure the highest level of accuracy, the report excludes the analysis/simulation studies for frequency response and inertia constant of the system.

Compensation devices for Short Circuit Power and Dynamic Reactive power requirement must be connected in the grid at the point/node of requirement whereas the devices installed for providing inertia can be connected at any point in the grid. Accordingly, based on the global experience, the possible strategic locations for installation of synchronous condensers in a transmission network can be near renewable generating stations, HVDC Stations, load centres etc. The location, type of compensation device and its specifications shall be finalized based on the system requirement which can be derived from the system studies with the planned renewable integration. Based on these system studies, the new compensation devices such as synchronous condensers can be tailored to meet the specific requirements and can provide the required system inertia, short-circuit strength and VAR support to the grid. Therefore, augmentation of the system with appropriate compensation devices, can make the grid performance at par with conventional power generation technologies, where active power is being generated from wind farms or solar parks and other requirements like system inertia, short circuit withstand capability, dynamic voltage support etc. are met by these devices.

CHAPTER-1

INTRODUCTION

1.1. Background

The study and report submission on the use of existing conventional generators as Synchronous Condensers for grid stability aspects of short circuit power and inertia was carried out as a part of Internal MOU of NTPC Engineering Department for FY 2021-22. Accordingly, the report was approved by NTPC management and was released for NTPC internal circulation/study in January 2022. Subsequently, the report has been updated in April 2024 considering the following:

i) Revised data and targets for non-fossil capacity
ii) Advantages of New Synchronous Condensers
iii) Use of existing Gas and Hydro/Pumped Storage plant generators as 'Synchronous Condenser'
iv) Technological advancements and other alternatives for grid stability
v) Policy changes in meantime

A group was also formed by CEA for examining the use of synchronous condensers in Indian Power System with respect to the technical, economic and regulatory aspects (first meeting of the group was held on 12.02.2021).

1.2. Introduction

As a part of carbon emission reduction mechanisms, many countries have adopted policies to increase the installed capacity of renewable generation, to either supplement or replace the existing thermal generation. With the planned rapid growth of renewable energy and withdrawal of conventional fossil fuel-based plants in the future scenario, there is a need to assess the impact that 'generation transition' shall have on the power system. The displacement of conventional generators with power electronic interfaced renewable generators may affect the system steady state and dynamic behaviour due the following:

- Reduction in power system inertia

- Reduction in short circuit power
- Reduction in dynamic reactive power reserves
- Reducing levels of synchronizing and damping torque
- Power Quality issues

These ancillary services have inherently been provided by the conventional generators and hence grid stability due to these ancillary services has never been an issue in the pre-renewable era. The renewable generators are integrated to the power system with the use of power electronic devices. These renewable generators connected through power electronic devices pose challenges to the power system as they cannot provide inertia, have limitations of providing short circuit power, reactive power and introduce harmonics in the power system. Despite the inverters of renewable energy farms offering dynamic reactive support to the grid in accordance with grid compliance standards, the available reactive power range from these devices remains a constraint.

The reduction in inertia will impact the network frequency control capability and the Rate of Change of Frequency (RoCoF) shall be higher with low inertia in the system. Further, if adequate system strength (Short circuit power) is not maintained in the system, voltage regulation capability, fault ride through performance, stability of system during the fault etc. is impacted. Further, it can also lead to insufficient fault current to reliably operate impedance and over current based protection schemes. Dynamic VAR reserves are required for maintaining the system voltage levels during the steady state and transient conditions.

One of the most suitable solutions for addressing the challenges of grid stability can be the installation of synchronous condensers in strategic locations. The synchronous condenser-based solutions can mitigate most of the challenges highlighted above with renewable penetration. Further, considering huge planned RE integration and possible retirement of old/inefficient thermal assets in the longer run, a need was felt for carrying out a study for re-purposing these retiring assets as synchronous condensers. Accordingly, technical details/changes required for conversion, advantages, challenges of repurposing these assets, technical details of new synchronous condenser installation, advantages of using new synchronous condensers over repurposing of retiring assets, layout requirements, cost recovery mechanisms etc. have been studied. Recently, Central Electricity Authority (CEA) has issued an advisory to all the Thermal Power Utilities not to retire or repurpose their coal-based power stations (units having capacity of more than 200 MW) before 2030 and to ensure the availability of thermal units after carrying out Renovation and Modernization (R&M) activities, if required, considering the expected energy demand scenario and availability of capacity in future. In view of the same, repurposing of retiring thermal power plants (of capacity of more than 200 MW) may not be possible before 2030. Further, thermal units having capacity less than 200 MW are expected to have challenges for repurposing due to their remaining life (as these generators are very old), limitation in providing required ancillary services (due to smaller rating), old design etc. Even though no thermal generators are scheduled for retirement until 2030, the substantial integration of renewable sources into the grid poses a challenge in operating the thermal units at or lower than their technical minimum. Consequently, it is conceivable that instead of running all units below/at their technical minimum, some units may have to be placed in reserve shutdown mode. Hence, system study needs to be carried out for understanding the impact of planned renewable energy generation into the grid.

Another aspect that has been studied in the report is the possibility of use of existing gas turbines as synchronous condensers. The gas turbine can be run either in ‘Generation mode’ or in ‘Synchronous Condenser mode’ with the provision of clutch arrangement. However, feasibility studies need to be carried out for provision of clutch based on the layout and equipment specific requirements. Further, details of using existing hydro/pumped storage plants as synchronous condensers have also been deliberated in the report.

The technical solution, policies and pricing mechanism need to be in place as early as possible for promoting investment in this area so that ancillary service providers are ready when there is a major shift from conventional generation to renewable generation.

1.3. Objective of the Study

The main objective of the report is as follows:

- Identify the challenges due to renewable integration.
- Identify the available solutions for these challenges.
- Identify solutions available in the market.
- Comparison of the existing solutions.
- Study for repurposing of existing coal-based thermal assets as synchronous condenser for grid stability.
- Identify challenges of repurposing thermal plants.
- Study of retrofit solutions for using gas plants in Synchronous Condenser mode.
- Advantages of new synchronous condenser installations.
- Technical details of synchronous condensers and associated systems
- Regulatory and cost recovery aspects for use of synchronous condensers for grid stability.
- Global Case studies for systems with high RE penetration.
- Global examples of synchronous condenser installations.
- Role of NTPC for synchronous condenser installations.

The report provides details of some of the possible solutions that can be adopted for grid stability for renewable integration. However, this does not imply that these are the only solutions. The readers can select any other alternative based on their specific requirements and analysis of the available solutions.

1.4. Organization of the Report

The report is organized into nine different chapters. **Chapter-1** covers the background of the study, introduction and objectives of the study. **Chapter-2** discusses about the challenges of renewable integration and covers overview of renewable scenario in India, future scenario/growth trajectory of renewable energy in India. Further, grid stability issues with the planned renewable integration have been discussed in the chapter. **Chapter-3** includes details about the available solutions for grid stability in the renewable era. A comparison between the FACTS devices (power electronic devices) such as SVCs, STATCOMs and rotating machines (synchronous condensers) has been indicated. Further, the technology advancements/upcoming solutions, synthetic inertia provision with BESS has also been discussed in this chapter.

Synchronous condensers technical details, components & their selection, layout requirements, capability curve, technical specifications have been highlighted in **Chapter-4**. **Chapter-5** includes details about repurposing retiring thermal units and gas power plants and use of hydro/pumped storage plants as synchronous condensers and provides details about modifications required, time in repurposing and comparison of new synchronous condenser installation with repurposing of retiring generators. Also, the challenges in repurposing of thermal power plants and advantages that new synchronous condenser have been highlighted in this chapter. In **Chapter-6**, regulatory and cost recovery aspects, requirement of uniform compensation mechanism, international practices for compensation of the ancillary services (inertia, short circuit power and dynamic reactive power) and components/equipment/facilities to be considered for calculating the cost of new synchronous condenser installation and re-purposing thermal plants have been discussed. **Chapter-7** provides detail about global installations of synchronous condensers and global grid failures due to renewable integration. In **Chapter-8**, simulation studies are included for understanding the effect of renewable integration on grid stability aspects of short circuit power. Simulation with and without the use of Synchronous Condenser is included in the case study. **Chapter-9** highlights the role that NTPC can play for synchronous condenser installations in India.

The conclusions and recommendations of the report have been detailed in **Chapter-10**.

CHAPTER-2

CHALLENGES OF RENEWABLE INTEGRATION

2.1 Overview of Renewable Scenario in India

Presently, the total installed capacity of India is around 441.969 GW (as on 31.03.2024). The capacity from fossil fuel-based sources (coal, lignite, gas, diesel etc) is around 55%, hydro is around 10.6%, renewables is around 32.5% and nuclear is around 1.9%. The details of present installed capacity (as on 31.03.2024) in India is as follows:

S. No.	Type	Installed Capacity (MW)	Percentage Share
1.	Fossil Fuel	2,43,216.87	55%
2.	Wind, Solar and other RE	1,43,644.51	32.5%
3.	Hydro	46,928.17	10.6%
4.	Nuclear	8,180	1.9%
	Total Installed Capacity	**4,41,969.55**	**100%**

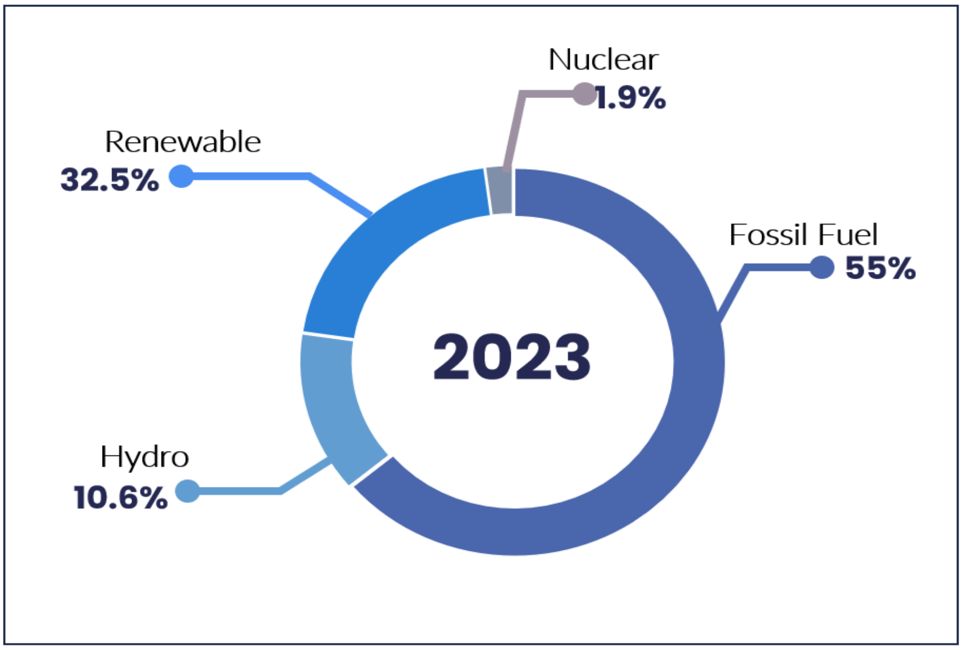


Figure 1: Generation Mix (as on 31.03.2024)

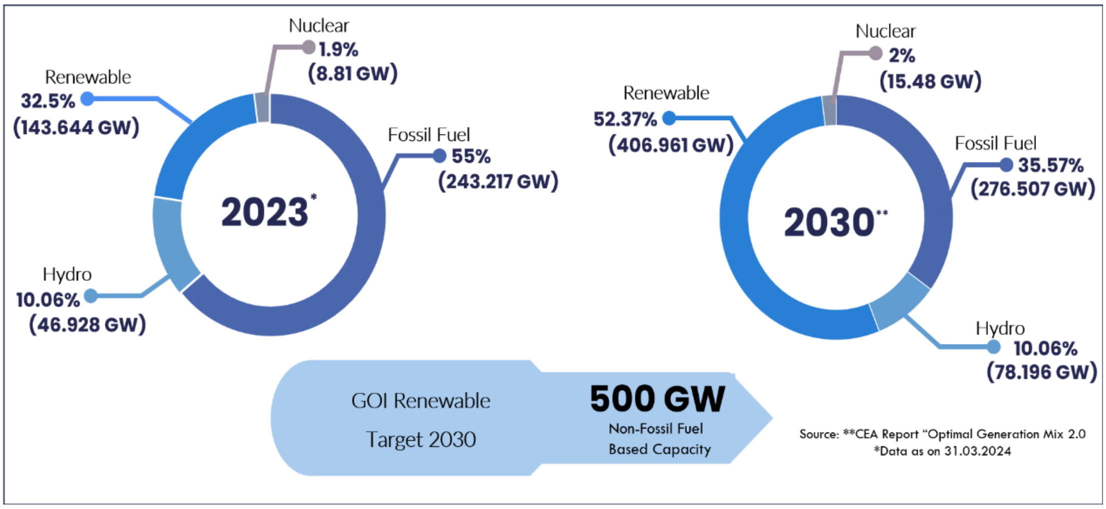
Data Source: powermin.gov.in

2.2 Future Scenario/Growth Trajectory of Renewable Energy in India

India is progressing in renewable growth and taking steps towards reducing carbon emissions to achieve the commitment of producing energy from non-fossil fuel-based sources as per COP26 commitments. As per the updated NDC targets, the country plans to reduce emissions intensity of its GDP to 45 percent by 2030 from 2005 level and has further set the target for cumulative electric power installed capacity from non-fossil fuel-based energy resources to 50% by 2030. Also, India is targeting installed capacity of 500 GW from Non-fossil-based sources by 2030.

The details of likely installed capacity mix of generation in 2030 (as per CEA report, Optimal Generation Mix 2.0) is as follows:

S. No.	Type	Installed Capacity (MW)	Percentage Share
1.	Fossil Fuel	2,76,507	35.57%
2.	Wind, Solar and other RE	4,06,961	52.37%
3.	Hydro including PSP	78,196	10.06%
4.	Nuclear	15,480	2%
	Total	**777,144**	**100%**



Source: **CEA Report "Optimal Generation Mix 2.0
*Data as on 31.03.2024

Figure 2: Generation Mix (2023 and 2030)

In FY 2023-24, generation from fossil fuel-based sources was around 76% of total generation whereas generation from renewable sources (excluding hydro) was around 13%. The projected generation in 2030 as per CEA report shall be around 52% from renewable sources (excluding hydro) and around 35% from fossil fuel-based sources. This change in the grid scenario can pose challenges for grid stability and reliability. As a result, additional systems may have to be installed to compensate the ancillary services inherently provided by the conventional generators for grid stability and reliability.

2.3 Grid Stability/Reliability Issues with Renewable Integration

India is constantly adding renewables into the grid and soon we shall come to a point where we start withdrawing conventional energy sources from the grid. Figure-3 provides details about the growth of RE and conventional generation in India in the last few years.

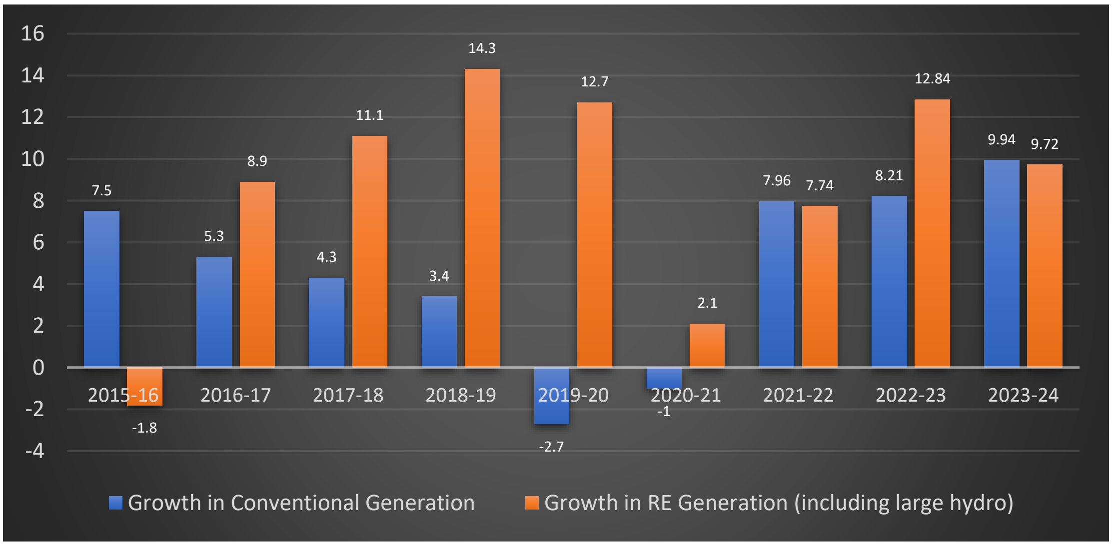


Figure 3: Growth in Conventional and RE Generation

Renewable generators are integrated to the power system using power electronic inverters. These RE generators present challenges to the power system as they cannot provide power system inertia, have limitations in providing short circuit power and reactive power which are the key elements of grid stability. On the other hand, conventional synchronous generators ensure stability of the power system facilitated by their fast, dynamic response system and instantaneous inertia response under contingency scenarios. The synchronous generators have large rotating masses and therefore can provide instantaneous inertia into the system for frequency regulation. Further, their ability to provide Short Circuit strength and Dynamic reactive power provides the required voltage support and overall power/voltage stability. Therefore, due to the combined effect of addition of renewables and withdrawal of conventional energy sources from the grid, the availability of these key elements for grid stability shall start diminishing. Considering these challenges, power system planning needs to be done for provision of critical key elements of grid stability in the renewable era for ensuring a stable, reliable and sustainable grid with provision of appropriate compensation devices at strategic locations.

2.3.1 Inertia

One of the most important challenges of renewable integration is the provision of inertial stability provided by the conventional generators. Inertia of a power system mainly comprises of the energy stored in the rotating mass of synchronous generators, with a partial contribution from frequency sensitive load. The speed of rotating synchronous generators and grid frequency is magnetically locked, therefore the rotational energy (Kinetic energy) stored in the conventional generators, resists any sudden change in the grid frequency by releasing stored kinetic energy to the grid. The kinetic energy of the conventional generators acts like a shock absorber to keep the grid frequency in control during sudden supply-demand changes over very short periods. In the absence of inertia from the system, there may be frequent df/dt trippings during the load fluctuations, and this may even lead to cascading outages in the system.

The renewable generators are connected to the grid through inverters using power electronic devices and hence they cannot provide the inertia for grid stability. As a result, the rate of change of frequency (RoCoF) will become larger with renewable penetration. The lower rate of change of frequency (RoCoF) indicates the robustness of a power system to withstand sudden system imbalances. If the RoCoF cannot be kept within acceptable boundaries, the need for load shedding will increase. Increased RoCoF can also lead to cascading protection trips and cause wider system outages. As a result of the changing grid scenario, there is a need to monitor inertia and figure out means to add inertia into the system. High RoCoF values can also result in inaccurate operation of UFLS (Under Frequency Load Shedding) schemes or potentially collapse of the system in the worst-case scenario. The reduction in power system inertia also has an impact on the transient stability. The reduction of power system inertia reduces its ability to damp out the oscillations. Also, ROCOF based protection is likely to be activated more often in a system with low inertia.

A snapshot of the simulation study carried out by Texas System operator for the impact of system inertia on the RoCoF is shown is Figure-4 below.

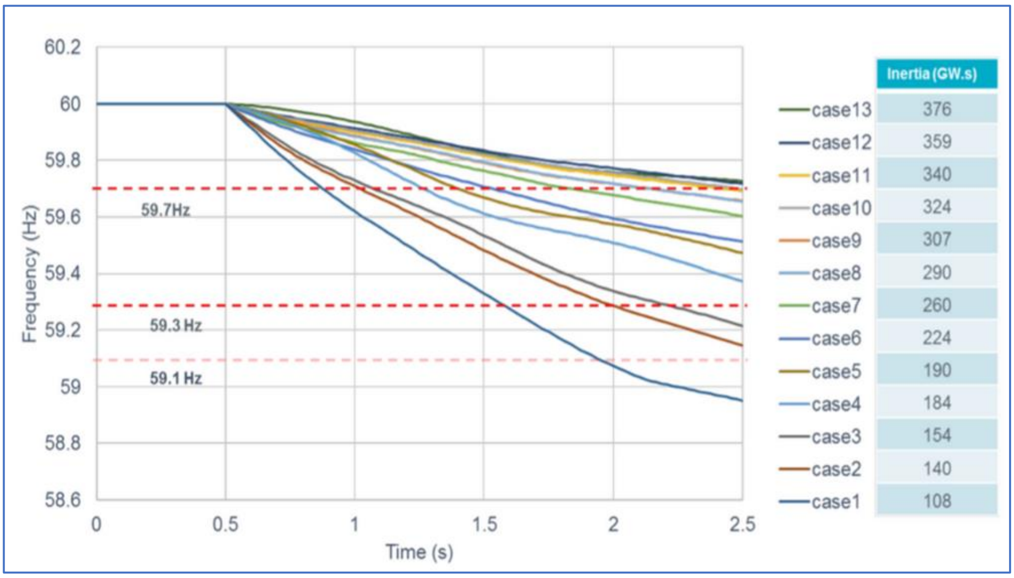


Figure 4: Snapshot of Simulation Studies by Texas System Operator

Further, some of the key points related to inertia highlighted in the report submitted by POSOCO (Now Grid India) in collaboration with IIT Bombay on “Assessment of Inertia in Indian Power System (January 2022)” are as follows:

- System inertia to be considered as a critical parameter in planning and operation of the future Indian grid, say beyond 2027, with high penetration of non-synchronous generating resources.
- Policy initiatives to encourage deployment of synchronous inertia sources, such as synchronous condenser, and hydro generation, besides provisions for synthetic inertia to be provided by non-synchronous resources, for ensuring adequacy of system inertia.

- Technical definitions of system inertia and associated terms to be incorporated in the regulations.

- Tools for Inertia estimation, online measurement and forecasting need to be explored.
- Studies may be initiated to assess the minimum inertia requirement for secure and stable operation of the Indian grid under different operating scenarios.

Some of the available inertia support technologies are as follows:

- Synchronous Condenser
- Synchronous Condenser with Fly wheel
- Battery Energy Storage System (BESS)
- Synchronous Condenser with Battery Energy Storage System (BESS)

2.3.2 Short Circuit Power

It is the power that can be provided by the network in case of a fault. The Short Circuit Power/SCR (Short Circuit Ratio) represents the ability of a bus to withstand the voltage fluctuations in response to a fault. The SCR is defined as the ratio of Short Circuit MVA available at the bus to the MVA rating of all the generators connected at the bus. Higher the short circuit power/Short Circuit Ratio, the stronger is the system. In the pre-renewable era, the short circuit power has inherently been provided by the conventional synchronous generators. However, in the upcoming scenario i.e., increase in renewable energy and significant decrease in conventional generation, there may be a significant decrease in short circuit power which needs to be compensated. The reason for decrease in short circuit power is that conventional generators produce significantly high level of short circuit power as compared to renewable generators which are limited by the rating of the electronic components. In case of renewable generators, power is fed into the network through inverters, so there is a limitation of current. The short circuit current provided is not enough to detect fault and results in continuous feeding of fault.

System studies need be carried out to identify areas of the network where additional short circuit support is required for injecting the planned renewables into the grid. Also, additional systems which can inject short circuit power into the grid need to be explored in the changing grid scenario. Synchronous condensers can be one of the most suitable solutions for the provision of short circuit power. The same has been discussed in detail in other chapters of this report.

2.3.3 Reactive Power Compensation

Higher penetration of power electronics integrated renewable generators into the power system not only increases the reactive power requirements, but also impacts the overall system performance. Most of the countries around the globe have started defining the reactive power requirements for renewable generators for maintaining the fault ride through capability, reactive power management and voltage control. Reactive power impacts the steady state voltage as well as voltage recovery after the system disturbances. Accordingly, there is a need to specify both steady state and dynamic reactive power requirements in renewable energy generators. Transmitting reactive power over long distances is ineffective, therefore reactive power support must be provided locally. FACTS devices such as STATCOMs etc. are being presently used by the system operators for providing dynamic reactive power support due to their fast response. Possibility of using other compensation devices for dynamic reactive power, which can provide other ancillary services also, need to be explored.

With large scale integration of renewables and withdrawal of conventional energy from the grid, there shall be significant decrease in reactive power levels/reserves which may lead the grid to become unstable. During the transient fault conditions, low inertia wind turbines and inertia less solar generation may not be able to provide the required voltage support to the grid without proper reactive power support mechanisms. Also, long distance transmission corridors (between load centres and renewable generators) may become unstable during system contingencies/faults due to lack of reactive power.

Therefore, it becomes important to identify locations for installation of suitable compensation devices for provision of inertia, short circuit power and dynamic reactive power reserves to ensure a stable and reliable system. System studies need to be carried out considering the planned renewable integration for provision of appropriate compensation devices for these ancillary services.

CHAPTER-3

SOLUTIONS FOR GRID STABILITY IN RENEWABLE ERA

The available technologies for grid stability can broadly be classified as FACT devices i.e., Flexible AC Transmission System and rotating machines which include the conventional generators and synchronous condensers. The FACT devices are the power electronic devices which control the capacitors and reactors for reactive power.

3.1 FACTS Devices

FACTS devices (Flexible AC Transmission System) are static power electronic devices installed in AC transmission system to increase the power transfer capability, improve the stability of the network etc. Following FACTS devices are available for providing reactive power compensation:

- SVC (Static VAR Compensator)
- STATCOM (Static Synchronous Compensator)

These devices cannot provide inertia and have limitations of providing Short Circuit Power. Further, other new technologies such as E-STATCOMS, Grid forming inverters etc. are in development stage. These technologies may also be considered for implementation after techno-commercial studies, demonstration of abilities to provide ancillary services based on the system requirement and reaching the required technology readiness level.

3.1.1 Static VAR Compensator

The Static VAR Compensator is a device of the Flexible AC Transmission System (FACTS) family. It uses the power electronic devices to regulate the voltage in the transmission system by absorption and generation of reactive power. The variation of reactive power is performed by switching the capacitor and reactor banks connected on secondary side of the coupling transformer. The capacitor bank is switched ON and OFF by thyristor switched capacitors (TSCs). The reactors are either switched ON/OFF through TSR (Thyristor Switched Reactors) or can be phase controlled i.e., Thyristor Controlled

Reactors (TCRs). Typical Single Line Diagram and simplified block diagram indicating SVC control system is as follows:

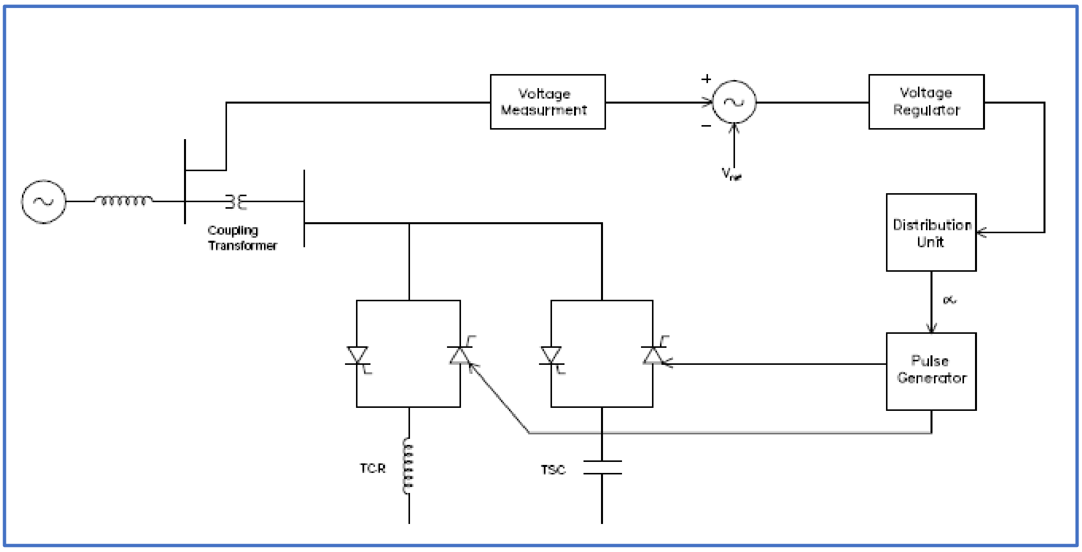


Figure 5: Typical SLD and Block Diagram of SVC

The Control System consists of:

- **Measuring Unit:** Measures the voltage to be controlled.
- **Voltage Regulator:** Uses the error signal to determine the reactive power requirements (absorption or generation) to maintain system voltage.
- **Distribution Unit:** Determines the TSCs/TSRs to be switched ON and the required firing angle.
- **Pulse Generators:** Pulse Generators are used to send the required pulse to the thyristors.

3.1.2 STATCOMS (Static Synchronous Compensators)

STATCOM is a power electronic device using forced commutated devices like IGBT, GTO etc. to control the reactive power flow in a transmission system. Synchronous in “STATCOM” signifies that it can absorb or generate reactive power in synchronism with the demand to stabilize the system.

A typical Single Line diagram of STATCOM is given below:

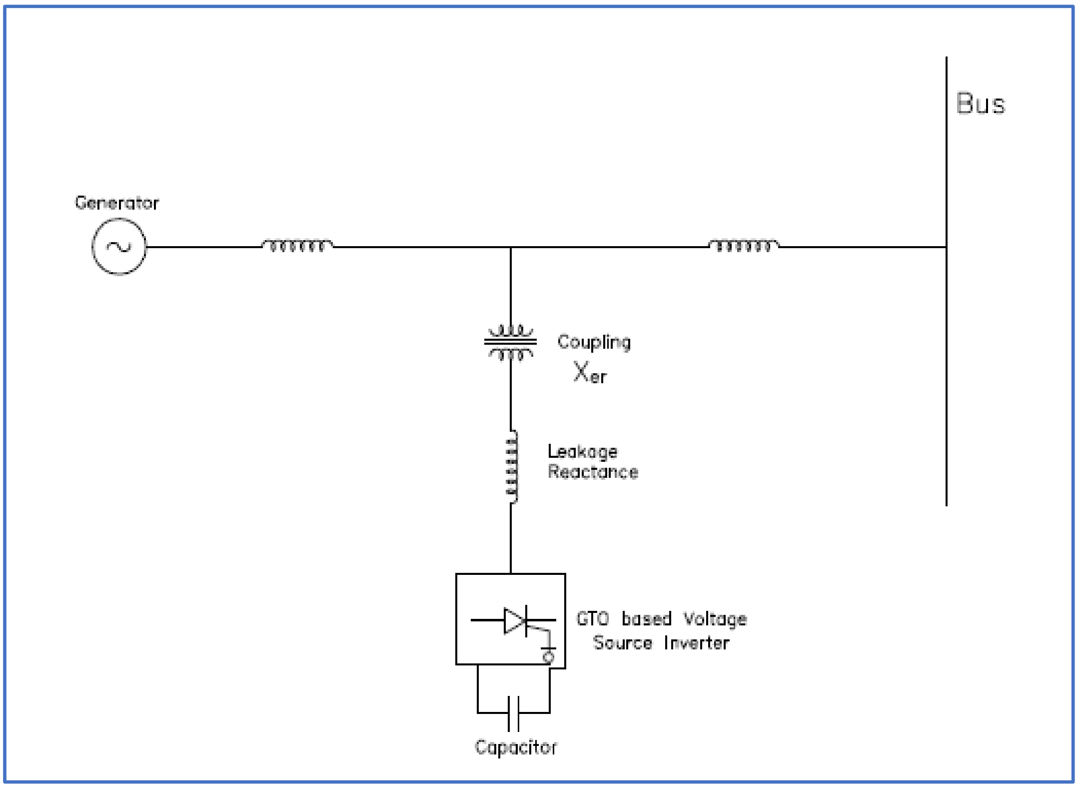


Figure 6: Typical SLD of STATCOM

A STATCOM has the following components:

- **Voltage Source Converter:** Voltage Source Converter is used to convert DC input voltage to an AC output voltage (Can be GTO Thyristors or IGBT).
- **Capacitor:** Used to supply constant DC voltage to Voltage Source Converter (VSC).
- **Coupling Transformer:** Coupling transformer is provided between VSC and Power System.

Operation of STATCOM

In the figure-7 below, V_1 represents the Inverter output voltage and V_2 represents the system voltage.

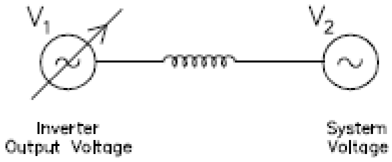
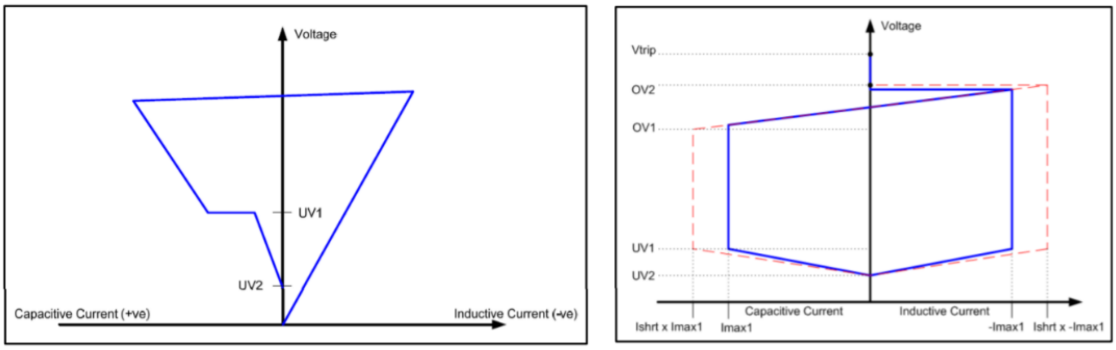


Figure 7: Understanding operation of STATCOM

In case the reactive power demand in the system increases, STATCOM increases its output voltage V_1. As $V_1 > V_2$, reactive power flows from STATCOM to power system. If voltage of Power System increases, STATCOM decreases output V_1. So reactive power flows from system to STATCOM. Limitation of STATCOM to supply or absorb reactive power is governed by the current carrying capacity of forced commutated devices (IGBT/GTO).

Comparison of STATCOM and SVC response:

The reactive power compensation provided by a STATCOM is more than SVC because at a low voltage limit, the reactive power drops off as the square of the voltage for the SVC but drops off linearly with the STATCOM. This makes the reactive power controllability of the STATCOM superior to that of the SVC, particularly during times of system distress. Typical VI characteristic of SVC and STATCOM is given in Figure-8 below.



SVC **STATCOM**

Figure 8: Typ. VI Characteristic of SVC and STATCOM

In case of fault in the network, maximum reactive output current of STATCOM will not be affected by the voltage magnitude (constant current characteristic). On the other hand, SVC's output is proportional to the square of the voltage magnitude. Therefore, SVCs capacity to provide reactive power to the system decreases when it is needed the most. STATCOMs in comparison can inject maximum current at reduced voltage also.

3.2 Rotating Machines

3.2.1 Synchronous Generators

The synchronous generators that are being used in thermal and hydro plants inherently provide inertia, short circuit power and dynamic reactive power as per the system requirement and hence help in maintaining the strength of the power system.

3.2.2 Synchronous Condensers

A synchronous condenser is a conventional solution that has been used for many years for regulating reactive power before there were any power electronics compensation systems.
A synchronous condenser is a DC-excited synchronous machine whose shaft is not attached to any driving equipment. This device provides the following:

- Improved voltage regulation and stability by continuously generating/absorbing reactive power.
- Improved short-circuit strength.
- Frequency stability by providing synchronous inertia.

Synchronous condensers can produce or consume reactive power depending on the voltage requirement of the system using Automatic Voltage Regulator (AVR) . The synchronous condensers help in controlling the voltage levels in a network during normal operations (thereby improving static stability, increasing active power transport capacity) and during transient conditions i.e., during major disturbances in the network.

The technical details and components of synchronous condensers shall be discussed in the upcoming chapters.

3.3 Hybrid Solutions

Hybrid solutions are also emerging as one of the solutions for provision of the required ancillary services in the renewable era. The hybrid solution can be a combination of devices such as STATCOM and Synchronous Condenser, STATCOM and Battery energy storage system (BESS), Synchronous Condenser and BESS etc. The hybrid solutions can be selected based on the system specific requirements wherein specific benefits of each device in the hybrid solution can be utilized for providing the required support. Further, other new technologies such as E-STATCOMS, Grid forming inverters etc. are in development stage. As per the information available, E-STATCOMS are formed by integrating an energy storage system/super capacitor with a STATCOM and therefore they may contribute to active and reactive power support to the grid. No commercial installation for E-STATCOM is presently known. These technologies can be considered for implementation only after detailed techno-commercial studies, analysis of ability to provide ancillary services based on the system requirement and reaching the required technology readiness level.

3.3.1 STATCOM with BESS

Battery energy storage system (BESS) in combination with STATCOMs have emerged as one of the possible solutions for active power control along with the compensation for reactive power. The integrated system compensates the reactive power and in addition stores energy in the storage system when generated power exceeds the demand and injects the stored power when the same is required in the system. However, the inertia response provided by STATCOM with BESS is not instantaneous as synchronous machines due to the use of complex measuring/comparing system (rate of change of frequency). Therefore, maintaining the Rate of Change of Frequency (ROCOF) within prescribed limits using hybrid solution of Static Synchronous Compensators (STATCOMs) and Battery Energy Storage Systems (BESS) during grid dynamic events will be a key area of study. EMT simulations will be necessary to accurately assess their behaviour under these conditions. Further, the ability to provide short circuit power is limited due to the use of power electronic components (very expensive/high rated components shall be required for providing required levels of short circuit power).

3.3.2 Concept of Synthetic Inertia

The term Synthetic Inertia is used when inertia is not available from rotation of equipment. The provision of synthetic inertia is a specific control of power converters characterized by absorption or injection of electrical power proportional to the frequency derivative. Synthetic inertia can be provided by Battery Energy Storage Systems (BESS) or by solar PV systems. Solar PV systems can provide inertia by keeping a margin in the solar power plant and generating power at lower levels than that can be generated at any point of time. In such a case, a part of the output of renewable power station is sacrificed and used to deliver Synthetic inertia whenever a frequency transient event occurs. However, the inertia response provided by STATCOM with BESS is not instantaneous as synchronous machines due to the use of complex measuring/comparing system (rate of change of frequency). Synchronous condenser performance is excellent to handle transient period voltage and frequency stability. BESS can support the dynamic frequency stability by giving required energy for short period limited (as per the battery rating). STATCOMs can provide dynamic voltage stability.

3.4 Comparison of Available Technologies for Grid Stability

A comparison of the some of the available technologies (SVC, STATCOM, Synchronous Condensers, BESS + Synchronous Condenser) has been prepared based on the literature and technical details available. Comparison based on the support provided is in included in Table-1, technical performance is included in Table-2 and lifetime/space requirements/manufacturing facilities etc. is given in Table-3. Specific details related to E-STATCOM/some other devices are presently not available and therefore the same is not included in the comparison table. However, E-STATCOM performance is expected to be similar to hybrid solution of STATCOM and BESS.

Table 1: Comparison based on the support provided:

Support	Synchronous Condenser	STATCOM	STATCOM with BESS	SVC
Inertia (Frequency Stability)	YES	NO	YES (Slow Response time than Syn. Con)	NO
Dynamic Reactive Power Support	YES	YES	YES	YES
Short Circuit Power	Very High	Very Limited	Very Limited (Due to cost limitation)	Very Limited
Overload Capacity	Very High 200% for 12 sec	No/expensive highly overrated components	Very Limited (Due to cost limitation)	No

Note: The ability of STATCOMs, SVCs to provide short circuit power/overload capacity is limited due to the capacity of Power electronic components. Further, based on the discussion with the vendors, the cost of STATCOMs, SVCs and BESS for providing same short circuit support/overload capacity as synchronous condenser is expected to be much higher.

Table 2: Comparison based on the Technical Performance:

Technical Performance	Synchronous Condenser	STATCOM	STATCOM with BESS	SVC
Response time for frequency support	Instantaneous (Rotating Inertia)	No	Limited (due to use of power electronic devices)	No
Response time for voltage regulation	Fast (Sub-Transient behaviour of generator)	Fast (Use of power electronic components)	Fast (Use of power electronic components)	Medium
Full Load Losses	1.5%	1%	1%	1%
CAPEX (for frequency support)	Low	No Frequency support	Very High	No Freq. support
CAPEX (for reactive power support)	Medium	Medium	High	Low
CAPEX (for short circuit power support)	Low	Very High	Very High	Very High

Table 3: Comparison based on the Space Requirements/ Life/ Manufacturing Facilities etc.

Other Features	Synchronous Condenser	STATCOM	STATCOM with BESS	SVC
Space Requirements	Compact	Medium	Large	Large
Technology Readiness	Proven	Proven	Not Proven (as hybrid)	Proven
Lifetime	30 years (min.)	30 years	30 years and battery replacement after 50,000 hrs (approx..)	30 years
Harmonics	No	Yes	Yes	Yes
Indigenous Manufacturing	Yes	STATCOM, SVC: Presently being imported. BESS: Limited indigenous manufacturing facilities		

From the comparison of the available technologies, it is observed that synchronous condensers are one of the most optimized and strongest technical solution to deal with problems of low inertia, short circuit power and reactive power requirement due to changing grid scenario. However, selection of the compensation device shall be based on the system specific requirement and ability of the selected device to respond to the required ancillary service. Also, pilot installation of each type of compensation device (if not installed earlier) in India may be considered based on the preliminary techno-commercial studies to compare actual performance of these devices in the Indian Power System Scenario.

Augmentation of power networks with appropriate compensation device and installation of the same at strategic locations (based on the system studies) can make the system performance at par with conventional power generation technologies, where active power is being generated from wind farms or solar parks and other requirements like ‘system inertia, short circuit withstand capability and dynamic voltage support are met by these devices.

CHAPTER-4

TECHNICAL DETAILS OF SYNCHRONOUS CONDENSERS

4.1 Operation of Synchronous Condenser

Synchronous Condenser is a conventional solution that has been used for many years for regulating reactive power before there were any power electronic compensation systems. Synchronous condenser can be considered as a synchronous generator without a prime mover or a synchronous motor without load. The design, controls, excitation system etc are similar to a synchronous generator. The synchronous condenser can provide voltage regulation by absorbing or generating reactive power, provide the sufficient short circuit power and instantaneous inertia to the power system. The Synchronous Condenser machine has a specific machine design, in which higher Short Circuit power can be delivered at the point of connection by reducing its sub-transient reactance saturated value. The generation/ consumption of VARs is achieved by controlling the excitation current. For operation as a synchronous condenser, the unit draws active power from the system. Also, the Synchronous Condenser can be coupled with a large flywheel to provide higher inertia to the power system as per the system requirement.

The figure below represents a typical synchronous generator capability curve of 588 MVA, hydrogen cooled generator. The area highlighted in red in the curve is the region where the synchronous condenser operates.

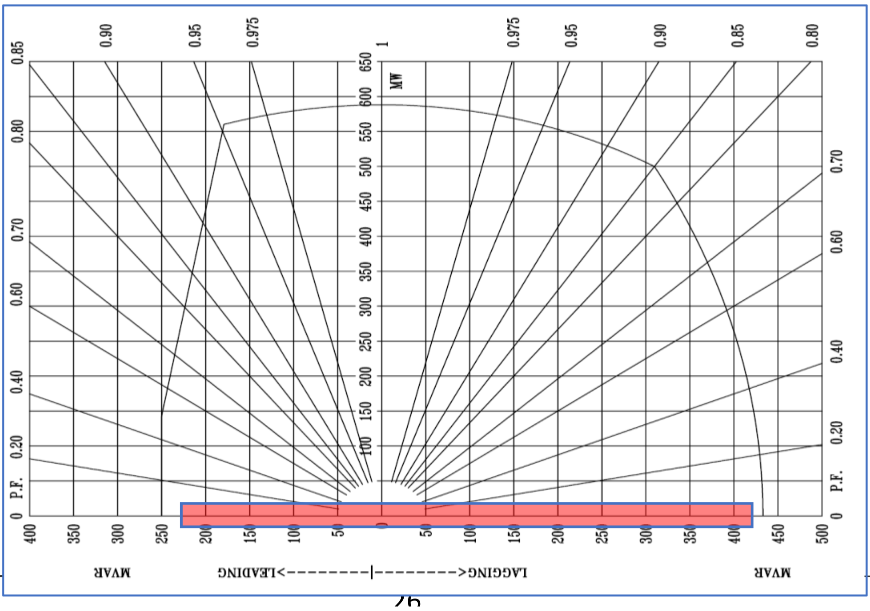


Figure 9: Typical Capability Curve of a Synchronous Machine

The operation of synchronous condenser is along the reactive power (MVAR) axis. As per the capability curve, the above machine can be used as a synchronous condenser with reactive power range from + 425 MVAR to - 220 MVAR (approx.). This represents the range over which this synchronous condenser can operate and support the grid during steady and transient state. The operation with positive MVAR means operation with an inductive load (lagging) i.e., providing reactive power in the system. On the other hand, operation with negative MVAR means operation with capacitive load (leading) i.e., consuming reactive power from the system.

4.2 Components of Synchronous Condenser

The typical components of a synchronous condenser are similar to a synchronous generator. Some of the typical components of synchronous condenser are listed below:

- Synchronous Machine
- Cooling System
- Excitation System
- Lube Oil System
- Step-up Transformer
- Auxiliary Transformer
- Starting Mechanism (Pony Motor/SFC)
- VFD (in case pony motor is used)
- GCB (in case of SFC)
- MV/LV Switchgear
- IPBD connecting Generator and Step-up Transformer
- Switchyard Bay for connection to grid

4.3 Cylindrical Rotor Type Machines

These machines are generally 2 pole or 4 pole with rotating speed of 3000 rpm (for 50 Hz, 2 pole machines) or 1500 rpm (for 50 Hz, 4 pole machines) and can be designed for a capacity of 5 MVA to 1000 MVA. Air cooled systems can be provided in machines up to 200 MVA, whereas for 200-600 MVA machines, hydrogen cooling system are generally provided. For hydrogen cooled machines, additional hydrogen cooling system and seal oil systems must be provided. The seal oil system is provided to prevent the escaping of hydrogen gas from the machine . For higher rating machines i.e., above 600 MVA, stator water cooling system is provided along with hydrogen cooling. In such machines, rotor and stator core is cooled by pressurized hydrogen gas, while the stator winding is cooled by water. These machines are horizontally mounted machines.

4.4 Salient Pole Machines

The salient pole machines can be 4 to 64 pole machines pole with corresponding rotating speed of 1500 to 93.75 rpm. The capacity of these machines can range from 0.5 MVA to 800 MVA and are air cooled. The salient pole machines can be horizontal or vertical mounted.

4.5 Synchronous Condenser with Flywheel

Synchronous condensers can be used for providing the inertia required in the system. The inertia provided by a synchronous condenser can be improved by providing a flywheel in the system. A flywheel is a rotating cylinder that is connected to the rotor shaft. Fly wheel is connected to the rotor shaft and requires an additional bearing. For designing the flywheel for obtaining the required inertia, rotor Diameter/Length ratio is maximized. Increasing the diameter reduces the overall length, which reduces the bearing losses, forging costs and civil works. However, the diameter cannot exceed a given limit due to the mechanical stress. Therefore, calculation of mechanical stresses at higher rotational speed and other design parameters needs to be carried out using available modelling/design tools.

The relation between the inertia constant and with Moment of inertia of the rotating mass and Rate of Change of Frequency (RoCoF) with inertia constant is given below:

$$H = \frac{\frac{1}{2}J\omega^2}{MVA}$$

H = Inertia constant in MWs / MVA
J = Moment of inertia in kgm^2 of the rotating mass
ω = nominal speed of rotation in rad/s
MVA = MVA rating of the machine

$$\frac{\partial f}{\partial t} = \frac{\Delta P}{2H}$$

$\partial f/\partial t$ = Rate of change of frequency
ΔP = MW of load or generation lost
$2H$ = Two times the system inertia in MWs / MVA

4.6 Selection of Step-up Transformer

The synchronous condenser output voltage may vary from 13-28 KV. Therefore, the synchronous condenser is connected to the grid through a step-up transformer. The transformer impedance has an impact on the short circuit power and reactive power output that can be provided through the synchronous condenser. Therefore, the impedance of the transformer needs to be selected according to the short circuit and reactive power requirements.

4.7 Excitation System

The excitation system must be designed considering the worst-case transients. For a synchronous condenser, a critical field current value is defined, which is the current required to maintain a nearly zero stator current at unity power factor. At this field current, the machine absorbs only real power from the system to overcome the windage, friction and copper losses. When the field current is reduced below the critical field current value, the machine becomes under excited and consumes reactive power from the system. Further, when the field current is increased above the critical field current value, the machine becomes over excited and supplies reactive power into the system. The ability of machine to supply reactive power into the system is limited by rotor heating limit (due to high field current). Similarly, the ability of machine to absorb the reactive power by the synchronous condenser is limited by core end region heating limit. The excitation systems have to be provided to meet the response characteristics as per the system requirement and operate the machine within the capability limits.

4.8 Starting Mechanism of Synchronous Condensers

As there is no prime mover with synchronous condensers, a mechanism is required for speeding up the synchronous condenser to the network speed for synchronization with the grid. The most common methods employed for starting of synchronous condensers are as follows:

- Static Frequency Converter
- VFD with pony motor

Static Frequency Converter (SFC):

For operation of synchronous condensers, static frequency converters provide a source of adjustable voltage/frequency for starting of synchronous condensers. SFC consist of converter, DC reactor and inverter. The converter converts 3 phase AC from grid (fixed voltage and frequency) to DC. The inverter is used to convert this DC voltage to variable voltage/frequency AC that is supplied to synchronous machine during the starting process. DC reactor connected in between converter and inverter acts as a filter to reduce the harmonic currents and ripple.

SFC accelerates the synchronous condenser to a speed higher than the rated speed (around 105%). Once the rated speed is achieved, the excitation system increases the field voltage to achieve the rated voltage at terminals of the synchronous condenser. The SFC is switched off and synchronous condenser is synchronized with grid after matching of voltage, frequency and phase. A typical block/single line diagram for SFC connection is shown below:

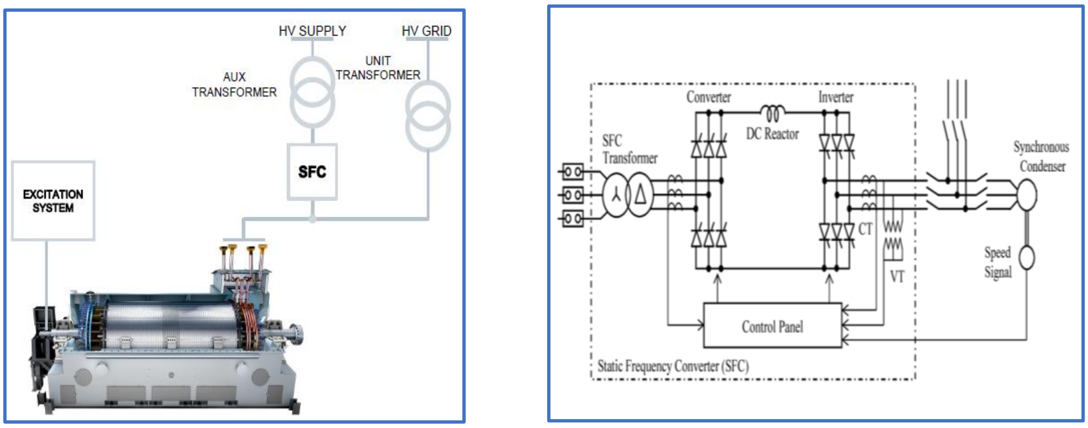


Figure 10: Typical SLD for SFC connection

Pony Motor with VFD:

Another method commonly deployed for starting of synchronous condensers is the use of pony motors. The pony motors should be adequately sized for providing the starting torque required to drive the heavy mass of synchronous condenser and increase the speed beyond the rated speed. This pony motor is started using a variable frequency drive (VFD).

When the rated speed of the synchronous condenser is achieved, the terminal voltage of the synchronous condenser is increased with the help of excitation system. The machine is synchronized after matching the output voltage, frequency and phase with the network. The pony motor is switched off after synchronization and keeps running idle thereafter.

Figure 11: Synchronous Condenser with Pony Motor

4.9 Selection of Generator Circuit Breaker

Generator Circuit breaker (GCB) shall be installed between synchronous condenser and step-up transformer. The characteristics of current fed by synchronous condenser after 3-phase short circuit at its terminals is significant to determine the GCB specifications. The main difference between the synchronous generator and condenser is their operating points during normal operation. Synchronous generators generally do not operate at zero power factor, whereas for synchronous condensers it is very important to consider zero power factor requirements. Another important factor is the lower inertia of synchronous condensers due to the absence of a prime mover. These factors can result in higher stresses on the GCB in terms of degree of asymmetry of the fault current in case of terminal fault and fault current due to out-of-phase conditions which can lead to delayed current zeros lasting several cycles.

4.10 Layout Requirements

The configuration/layout of a synchronous condenser installation is similar to that of a synchronous generator installation. However, synchronous condenser installations typically require less space than a similarly sized generator due to the removal of prime mover turbine and shaft components. In synchronous condensers, adequate space is required for installation of Flywheel, Static Frequency Converter (SFC) or a pony motor (starter motor) with variable frequency drive (VFD) to bring the machine up to synchronous speed from a standstill state. The major components of synchronous condenser installation are as follows:

- Synchronous Machine
- Excitation System
- Step-up transformer
- Generator Circuit Breaker
- Startup Mechanism
- Isolated Phase Bus Duct (IPBD)
- Auxiliaries
- Cooling System
- Control and Protection System
- Flywheel (as applicable)

The figure below shows a typical layout of a synchronous condenser installation.

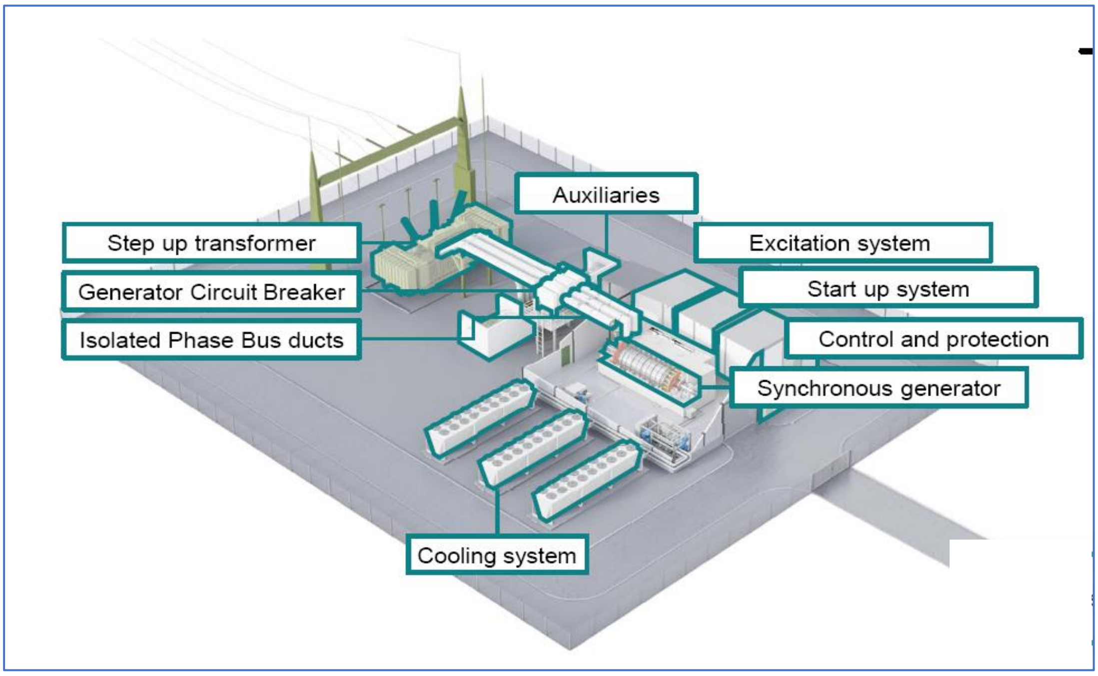


Figure 12: Typical Layout of Synchronous Condenser Installation

Figure 13: Overview of Synchronous Condenser Installation

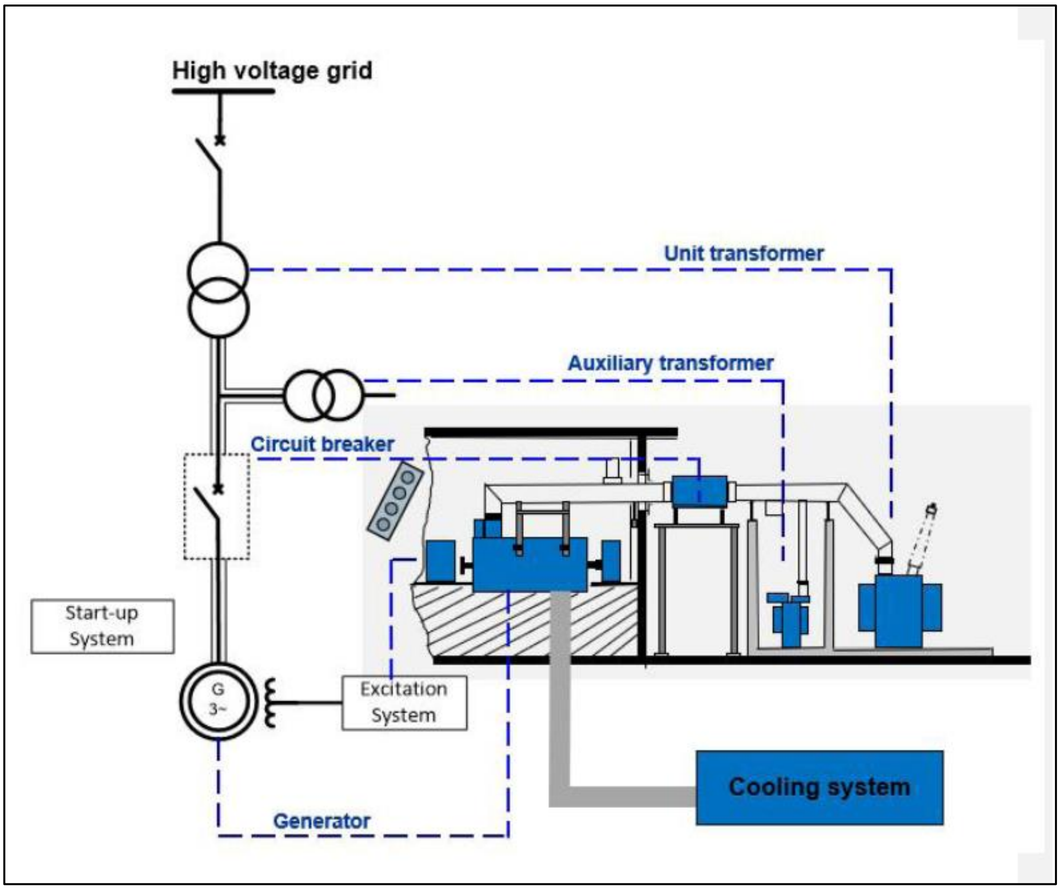


Figure 14: Schematic Configuration of a Synchronous Condenser

4.11 Technical Specifications of Synchronous Condensers

For designing a synchronous condenser, some of the details that are required are as follows:

1) Type and Rating:

- Maximum inductive reactive power at pf=0 in MVAR
- Maximum capacitive reactive power at pf =0 in MVAR
- Inertia Support in Kg-m^2
- Inertia Constant in MWs/MVA
- Kinetic energy of rotor at rated speed: unit is MJ (or MW.s)
- Terminal Voltage
- Speed
- Rotor Type: Cylindrical type or salient pole type
- Insulation class for Stator and Rotor Winding
- Cooling type

- Impedance (variation of Xd, Xd’ and Xd’’ should be specified)
- Overload capability
- Short Circuit withstand capability
- Step-up transformer impedance

2) Instrumentation and Monitoring System

- Number and location of temperature detectors for stator core, winding, air/water (as applicable), bearings, oil temperatures etc
- Pressure transmitters to monitor lubrication oil pressure, lift oil pressure etc.
- Speed sensors and overspeed protection
- Bearing and shaft vibration monitoring system
- Shaft current/voltage monitoring system

3) Auxiliaries

- Synchronous condensers have auxiliaries for lube oil and cooling water system.
- In case of hydrogen cooled synchronous condensers, requirement of seal oil and hydrogen gas system to be specified.

4) Excitation System

- High initial response type excitation system
- Static excitation system for fast response
- Excitation response time
- Excitation response ratio
- Excitation system ceiling voltage and ceiling currents

5) Requirements from Synchronous Condenser

- Reactive Power at PCC in MVAR
- Inertia/Kinetic Energy in MWs
- Short Circuit Power contribution at PCC in MVA

6) Power System Data

- Power System Studies and modelling
- R source and X source of the grid
- Short Circuit MVA/Short Circuit ratios of nodes

- Maximum and minimum grid voltage variations
- X/R ratio of the network at point of interconnection (POI)

7) Environmental conditions

- Maximum and minimum ambient temperature
- Altitude
- Humidity
- Seismic Requirements

Above details/guidelines indicated are the minimum requirements. The complete details required can be specified based on the system specific requirements provided by the system operator.

4.12 Possible Locations for Installation

System studies need to be carried out by the system operator to identify the best possible locations for installation of synchronous condensers. Both RMS and EMT (Electro Magnetic Transient) studies need to be carried as a part of the system studies. New synchronous condensers can be tailored to provide the required ancillary service based on specific requirements at a particular location/node as per the system studies. The key criteria of site selection include:

- Short circuit level
- Power system Inertia level
- Reactive power reserves in the area

Based on the list of global installations, some of the potential sites for installation of synchronous condensers is as follows:

- Areas remote from synchronous generators
- Areas with high inverter-based generations/solutions
- Areas close to metropolitan load centres
- HVDC stations

CHAPTER-5

REPURPOSING OF RETIRING UNITS

5.1 Retiring Units Scenario in India

Central Electricity Authority (CEA) has issued an advisory to all the Thermal Power Utilities not to retire or repurpose their coal-based power stations (units having capacity of more than 200 MW) before 2030 and to ensure the availability of these thermal units after carrying out Renovation and Modernization (R&M) activities, if required, considering the expected energy demand scenario and availability of capacity in future. In view of the same, repurposing of retiring thermal power plants (of capacity of more than 200 MW) may not be possible before 2030. Further, thermal units having capacity less than 200 MW are expected to have challenges for repurposing due to their remaining life (as these generators are very old), limitation in providing required ancillary services (due to smaller rating), old design etc. Even though no thermal generators are scheduled for retirement until 2030, the substantial integration of renewable sources into the grid poses a challenge in operating the thermal units at or lower than their technical minimum. Consequently, it is conceivable that instead of running all units below/at their technical minimum, some units may have to be placed in reserve shutdown mode. Hence, system study needs to be carried out for understanding the impact of planned renewable energy generation into the grid.

5.2 Repurposing of Retiring Thermal Assets

With a focus on achieving COP26 commitments and Net Zero Emission targets, addition of huge RE capacity as well as retirement of inefficient thermal power plants must to be carried out in the longer run. As discussed in the earlier chapters, this shall have an overall impact on the system strength and reliability. One possible approach for mitigation of these impacts can be the conversion of existing generator of fossil-fuel based plants (which are synchronous machines) as Synchronous Condenser. There are possible advantages of conversion such as the use of existing equipment and infrastructure, less upfront investment etc. However, there are many factors which need to be assessed when considering the life cycle cost for conversion of a retiring unit to a synchronous condenser. These include the technical considerations, power system requirements, conversion costs, commercial arrangements with the plant owners, guarantee/warranty of the old system and transportation, land, water availability and cost of these facilities etc. in case of relocation to a new area. On the other hand, new synchronous condensers can be tailored made as per system requirement, require lesser auxiliaries, have comparatively lesser footprint, require less quantity of water, have higher life expectancy etc. Therefore, life-cycle cost analysis needs to be carried out before taking the decision for repurposing the retiring assets as synchronous condensers.

Further, there are many factors which need to be considered and finalized before the conversion such as:

- Utility who will plan and initiate the conversion process (GENCO or TRANSCO or some other agency)
- Utility/Agency that will bear Capex for conversion
- Ownership of synchronous condenser plant
- O&M Modalities (O&M expenses and utility/agency that will run the plant)
- Requirement of transmission licence for running/re-purposing as synchronous condenser

5.3 Feasibility Studies

Feasibility Studies before conversion process needs to be carried out to ascertain various factors such as technical suitability of the location, health assessment of the existing equipment, cost benefit analysis etc.

Technical Suitability of the Location:

The technical suitability of the conversion location can be ascertained by the system studies which shall be carried out by the power system operator.

Based on the system studies (considering the planned renewable integration), the requirement of inertia, short circuit power or reactive power at a particular location shall be decided. It is not advisable to repurpose retiring generator by transporting to a new location considering the challenges related to transportation (to OEM works and from OEM works to new location), land availability and associated costs, water availability, civil and foundation costs, new/additional equipment as per layout requirement and complete set of auxiliary systems etc.

Technical suitability of the plant:

The retiring generator (both stator and rotor) needs to be assessed for healthiness of core and winding insulation by conducting the required tests. Accordingly, decision for re-winding may be taken. The design parameters of the generator need to be assessed for the critical system/network requirements at a particular location. The excitation system and insulation of the machine should be assessed for checking the adequacy of required ramp rate. The health and condition of the auxiliary equipment such as bearing lubrication system, hydrogen storage, seal oil system, cooling water systems, condition of bearing, step-up & auxiliary transformers, switchyard equipment, GCB etc need to be assessed. The step-up transformer should be assessed to check its suitability for the required ramp rate of loading, assessment of impedance of the transformer according to the short circuit and reactive power requirements.

Further, deliberations on layout requirements are also required for mounting of prime mover, placement of new thrust bearing, provision of Generator Circuit Breaker (GCB). Also, a study on the remaining life of all equipment needs to be carried out during the feasibility stage. Further, a review of the generator’s operating and maintenance history including major outages, winding insulation test reports etc. may be carried out.

Hydrogen cooled machines are good for conversion to synchronous condenser as insulation for the same deteriorates at a very low pace as compared to the air-cooled machines. The main cause of insulation ageing for hydrogen cooled generators is mechanical stresses. For an air-cooled machine, re-winding of stator as well as rotor may be necessary and shall be carried out based on the condition assessment.

A dynamic analysis of the shaft train must be performed since it is being significantly modified with the removal of turbine, addition of start-up device, relocation of thrust bearing etc.

After listing out all the tests, RLA (residual life analysis), modifications required for conversion, the cost benefit analysis shall be carried out to ascertain the economic viability of the conversion.

Basic Inputs for Feasibility Study

The following minimum details of retiring plant are required for the feasibility studies which shall be carried out for conversion to synchronous condenser:

- Single Line Diagram
- Generator, Generator transformer drawings and datasheets
- General Arrangement (GA) drawings of major electrical equipment
- Layout drawings
- Test certificates of major electrical equipment
- Generator cross section drawings, shaft outline
- Generator foundation drawings
- Schemes of excitation and protection system
- Generator IPBD layout drawings
- Schemes for auxiliary systems
- Operational data of generator (major outages, failures etc.)
- Rotor weight/inertia

5.4 Modifications Required for Retrofit

Most of the components existing in a retiring plant shall be utilized in the conversion process if the conversion is being carried out at the existing location. A typical generator of power plant is designed to operate and withstand all the electromagnetic & centrifugal forces at full load. When operating as a synchronous condenser, the forces experienced will be similar. The field winding will operate with the same voltage, current and mechanical forces. The stator winding current is less during operation as synchronous condenser, so stator heating and forces are much less. All generator auxiliary systems will be required for operation as synchronous condenser.

Some modifications shall have to be carried out for conversion of a conventional plant to synchronous condenser. The major modifications in the conversions process are described below.

5.4.1 Mechanical Modifications

- **Decoupling of Turbine from Generator:**
  As the turbine is not required for Synchronous Condenser operation, it is decoupled from the generator. The connection may have to be replaced with an extension shaft and bearing for stability. Further, based on the system requirements for inertia, feasibility studies for addition of fly wheel shall be carried out. The feasibility studies shall include the foundation, space requirements, shaft line calculations, integration of flywheel in existing system etc.
- **Thrust Bearing:**
  The main generator bearing on one end is to be changed to thrust bearing. The thrust bearing can be provided either on drive end or on the exciter end. In some cases, a stub shaft may have to be added for installation of thrust bearing.
- **Modifications in Lube Oil and CW systems:**
  Necessary modifications shall be carried out in Lube Oil and cooling water system to suit the new mode of operation. With removal of turbine rotors and their bearings, lubrication system will have to be evaluated for the flow requirements. Some turbine bearing lube oil lines may have to be blanked. With less heating in the lube oil system, raw water flow to the bearing oil cooler may have to be reduced.

5.4.2 Electrical Modifications

- **Provision of Starting Mechanism**:

  As the generator is not connected to turbine, a new starting mechanism shall be designed and implemented. The starting mechanism is provided for starting and synchronising the synchronous condenser to the gird. The following starting mechanisms are generally used:

  i) Static Frequency Converter
  ii) Pony motor with variable frequency drive (VFD)

  The above starting mechanism have been described in detail in previous chapters.

- **Excitation System:**

  For functioning as Synchronous Condenser, a fast response excitation system is required for responding to sudden variations in the gird. Generally, static excitations systems can handle the dynamic situations in a better way. The response time of brushless excitation system is slow as compared to the static excitation system. However, solutions are available in the market to convert brushless excitation system into a high response system. Depending upon the ramp rate requirements, modifications in excitation system shall be carried out.

- **Provision of Generator Circuit Breaker (GCB):**

  As per the Synchronous Condenser OEMs, it is recommended to provide a GCB in case of operation as synchronous condenser. Necessary studies regarding capability of EHV breaker to handle DC portion of current, layout constraints, electrical configuration, method of starting etc shall be carried out for deciding on the provision of GCB. Based on these studies and OEM recommendation, the requirement of GCB shall be assessed and finalized. LA and VT cubicles shall also be provided in case of GCB provision.

- Protection, monitoring & control system to be upgraded/suitably modified.

5.5 Repurposing of Gas Power Plants

Gas power plants can be converted to synchronous condensers by the provision of a clutch to connect the gas turbine and generator. When active power generation is required, the gas turbine is connected to the generator with the clutch closed. In this case, the gas turbine rotates the generator which creates active power which is delivered to the grid. When no active power is required, the gas turbine is connected to the generator with clutch closed, in order to start the unit. Once the generator is synchronised to the grid, the clutch is opened, and the gas turbine is stopped. The generator remains connected to the grid and is then operated as synchronous condenser.

For provision of clutch various constraints like space requirement, foundation modification, necessary adjustment/relocation/shifting of existing equipment, cost of modifications etc. need to be studied. Accordingly, feasibility study/check for each site needs to be carried out separately for provision of clutch in gas plants.

5.6 Using Conventional Hydro and Pumped Storage Plants in Synchronous Condenser Mode

Some hydro plants have the capability to operate as synchronous condenser in addition to their generation capabilities. Further, hydro plants mostly operate for peaking requirement. Therefore, they operate only in generation (or pumping mode) only for few hours in a day. These plants can be utilized as synchronous condensers in the remaining hours. On the electrical side, starting mechanism along with minor modifications in control, protection and excitation system will be required. The modifications required in mechanical system depends on the type of turbine used in the hydro power plant.

Hydro units with Pelton turbines can operate in Synchronous condenser mode without any modifications in the mechanical system. Hydro units with Francis turbines require dewatering of the runner for operating in synchronous condenser mode. Hydro plants with Kaplan turbine are not suitable for synchronous condenser mode of operation as dewatering of these units shall require very large amount of pressurized air and most of Kaplan units are run-of the river plants where they operate continuously and have not idle time to run in synchronous condenser mode.

Pump storage plants having reversible Francis turbine already have provisions of starting mechanism (for starting in pumping mode) and dewatering arrangement. Therefore, these plants can operate in synchronous condenser mode without any major modifications in the system.

5.7 Cost and Time in Repurposing of Retiring thermal units

The major cost in repurposing retiring generators as Synchronous Condensers (at its existing location) shall be in the following heads:

- Generator Rewinding Cost
- Drive Motor with VFD
- Provision of Generator Circuit Breaker (if required)
- Modification in excitation system
- Modifications in auxiliary system
- Provision of Thrust Bearing at new location
- Modifications in Generator Protection System (if required)
- Civil Cost for modification/new foundation
- Testing during feasibility stage
- Erection, Testing and Commissioning of all equipment

Most of the equipment required for synchronous condenser operation can be utilized from the equipment already existing in the retired plant. The time required for conversion which includes mechanical, electrical and civil modifications is approximately 15-18months.

5.8 Comparison of New Synchronous Condenser and Repurposing

Table-4: New Synchronous Condenser Vs Repurposing case

Parameters		New Synchronous Condenser	Repurposing of Retiring Generator
Technical Parameters	Location	Can be installed at locations according to system studies	Studies shall be required to ascertain effectiveness at existing location. In case of relocation, there shall be additional transportation, land and civil costs.
	Grid Requirements	Can meet exact grid needs	Shall depend on the original design of the machine
	Maintenance	May not require frequent maintenance	May require frequent maintenance due to ageing
	Losses/APC	Less due to new equipment and fewer auxiliaries	More in comparison to new synchronous condenser
	Technology	New technology, auxiliary systems required are less in comparison to repurposing.	Old technology, more auxiliary systems required
	Life Span/ Reliability	High due to use of new equipment	Less as compared to new synchronous condenser due to ageing
Cost	Generator	New machine cost	Only Rewinding Cost
	GT Bank	New GT bank can be tailor-made to suit system requirements.	Existing GT can be used subject to health assessment and suitability for required ramp rate of loading. Short circuit power and reactive power limitation may be there due to design impedance.
	GCB	New GCB	Existing GCB (if available) can be used. Else assessment shall be carried out for requirement of GCB.
	Static Excitation and Gen Protection System	New System	Existing system with some modification may be used
	Civil Foundation and Building	New Building and foundation	Existing building can be used with very less civil works. For transportation to a new location, new building and foundation shall be required.

	Land Cost	New Land	No land cost if repurposed at existing location. In case of transportation to a new location, land charges shall be applicable.
	EHV Bay	New Equipment required	Existing equipment can be used after health assessment if repurposed at existing location. In case of transportation to a new location, charges shall be applicable.
	Startup Mechanism	New Mechanism Required	New Mechanism Required
	Generator Bus Duct	New Equipment	Existing equipment can be used. In case of transportation to new location, new bus duct/modification as per layout requirements shall be required.
	Auxiliary System	New System	Use of Existing system minor modification
	HV and LV Systems	New System	Existing system can be used
	Erection, testing and commissioning	Shall be higher in comparison	Shall be lower in comparison
Time		15-18 months	15-18 months

Considering the CEA advisory not to retire old thermal plants, overall life cycle cost, challenges for re-purposing retiring coal based power plants such as life, challenges for transportation to OEM works for re-winding, guarantee/ warranty issues, efficiency, spare part availability, requirement of more auxiliary systems, higher foot print, water requirement, cooling requirement, Auxiliary Power consumption (APC) etc. and considerable advantages of new synchronous condenser installations highlighted in table-4 above, it is more advisable to consider new synchronous installations instead of re-purposing retiring thermal assets.

CHAPTER-6

REGULATORY AND COST RECOVERY ASPECTS

The increasing penetration of renewable energy into the grid poses many challenges to stability and reliability of the power system. The most important parameters for ensuring the system stability and reliability with integration of renewable energy into the grid are system Inertia, short circuit power and fast reactive power response. Renewable energy generators do not contribute to these ancillary services. Therefore, considering huge integration of renewables planned into the grid, additional equipment for provision of these ancillary services needs to be installed at strategic locations.

Presently, no concrete mechanism and regulations are available for compensating these ancillary services which are a need of the hour in renewable era. To ensure grid stability, reliability and to promote investment in the field of ancillary services, there is an urgent requirement to formulate cost recovery mechanism and regulation for these services.

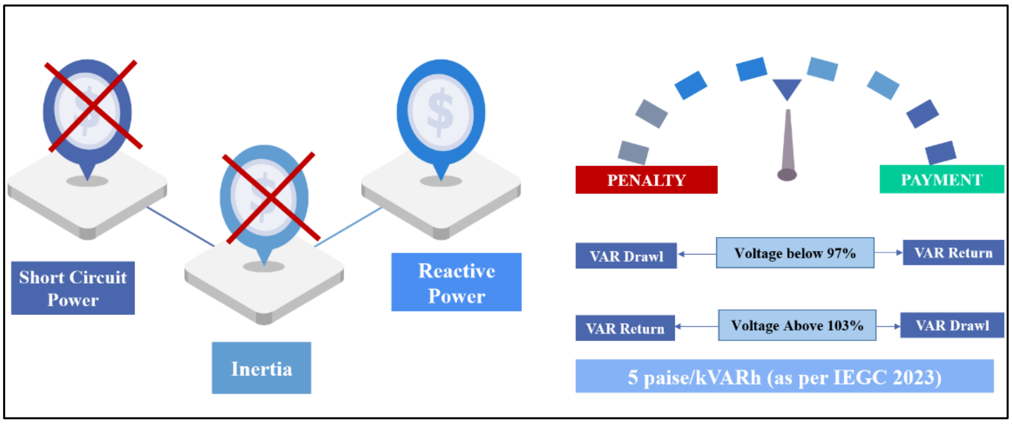


Figure 15: Present Compensation Scenario

6.1 Regulatory Support

Sound regulatory policies are necessary to ensure adequate short circuit power, inertia and reactive Power at a reasonable cost. The aim should be to develop regulations that ensure reliable, suitable and adequate ancillary services at strategic locations for overall stability of the power system at a realistic cost. The basic considerations while framing the regulations for these ancillary services shall be as follows:

- Assessment of short circuit power, inertia and reactive power requirements as per system studies.
- Provision of incentive/benefit/payment to all service providers of such ancillary services on non-discriminatory basis.
- Incentive for providing fast response ancillary services.
- Beneficiary of these ancillary services shall be charged for it.

Also, there is a need to develop uniform compensation mechanism for all such devices. Presently, in India, static compensation devices such as SVCs and STATCOMs are installed as “Grid Element” and the costs are being recovered as a part of the cost of basic transmission system. Whereas no such mechanism/cost recovery model is available for other compensation devices such as synchronous condensers.

To ensure that appropriate compensation devices are installed as per system requirement, a uniform recovery mechanism along with system simulation studies (with planned RE integration) is required. Similar cost recovery mechanisms can be treatment as ‘Grid Element’ or compensation based on the equipment capacity or development of tariff/regulations for sale in the open market. Further, there is a need to identify mechanism for selection and installation of compensation devices by utilities/agencies based on the ancillary requirement specified by the system operator on the identified locations. In such a case, cost recovery mechanisms/tariff provisions for these ancillary need to be identified in the regulations so as to ensure reliability and promote capital investment in these ancillary services.

6.2 International Practices

Presently, no concrete cost recovery mechanisms and regulations exist for compensating inertia and short circuit power. A tariff for compensating inertia has recently been introduced by EIR Grid. For reactive power compensation, different approaches have been adopted by the system operators. A brief about the ancillary services compensation mechanisms adopted by the system operators is presented below:

i) **Inertia compensation—EIR Grid (Ireland):** The basis of payment for Synchronous Inertial Response (SIR) is the calculation of the SIR available volume of the providing unit over a trading period. The Kinetic Energy and Minimum Generation of the providing unit form the basis for calculating SIR Available Volume when Synchronised to the Power System. The Service Provider will receive a payment for each MWs2 of SIR Available Volume for the Providing Unit in each Trading Period where Synchronised.

   The payment to the Service Provider for SIR Available Volume of the Providing Unit in a Trading Period is determined as:

   SIR Trading Period Payment = SIR Available Volume × SIR Payment Rate × Trading Period Duration

   SIR Payment Rate is the Payment Rate for SIR (expressed in €/MWs2h) applicable to SIR

   Details of complete payment mechanism can be assessed from System service regulations for EIR grid.

ii) **Reactive Power Compensation—ISO-NE:** ISO-NE operates qualified reactive resources to produce (or absorb) reactive power in order to maintain transmission voltages on the New England Transmission System. The reactive power compensation is based on following cost components:

   - Lost opportunity cost (LOC) component
   - Cost of energy consumed (CEC) component (Energy consumed to provide reactive power support)

- Capacity cost (CC) component (fixed capital costs and maintenance of equipment)

iii) **Reactive Power Compensation—NY ISO:** The NYISO calculates payments for voltage support service annually and makes payments monthly. For generators and synchronous condensers, the annual payment for voltage support service is equal to the product of calculated \$/MVAr and the tested reactive power capacity of the generator or synchronous condenser.

Synchronous condenser or qualified non-generator voltage support resource is compensated for the cost of energy it consumes to energize converters and other equipment.

iv) **Reactive Power Compensation—California System Operator (CASIO):** The California System Operator does not compensate for installation of reactive power capacity. Compensation is only provided for the opportunity costs of MVAR output outside its mandatory range.

v) **Reactive Power Compensation—Great Britain:** In GB, the acquisition of reactive power ancillary services by National Grid is based on three mechanisms: Obligatory Reactive Power Service (ORPS), Enhanced Reactive Power Service (ERPS) and through Transmission Constraint Management (TCM).

ORPS is a mandatory service for transmission connected large generators (over 50 MW) that are subject to the Grid Code. Generators receive a default payment for utilisation (£/Mvarh) that is updated monthly in agreement with market indicators. A mandatory service agreement (MSA) is required to be signed by generators for the provision of the ORPS.

ERPS is procured via tenders. It applies to generators whose reactive capability exceeds the minimum technical requirements of ORPS. Under EPRS, generators receive a capability price (£/Mvar/h) and/or a synchronised capability price (£/Mvar/h) and/or a utilisation price (£/Mvarh).

vi) **Reactive Power Compensation in Other Countries:** In the Netherlands, the network companies purchase reactive power locally through bilateral contracts with generators or through exchange with other network companies. Generators contracted for the reactive power service are paid for their reactive power capacity only. No payment is made for reactive power supplied.

The Australian ISO provides reactive power compensation to generators and synchronous condensers. The providers receive an availability payment, an enabling payment when dispatched and a compensation payment when their generators are restrained from operating according to market conditions.

In India, the reactive power compensation is provided a 5 paise/KVARh price on reactive power return/drawal when the voltage dropped below 97% or goes above 103% of nominal voltage.

In Canada, Shunt reactive compensation devices are installed by the transmission owner(s) to meet the forecast reactive power requirements as part of their transmission investment programs.

6.3 Selection based on the Cost Comparison

A cost comparison for different available technologies available in the market (providing exactly similar ancillary service) needs to be prepared for selecting the most suitable techno-commercial solution. The techno-commercial comparison shall also take into account the Technology Readiness Level along with performance data of commercial/pilot installation each of the compensation device.

Further for estimating the price of new synchronous condenser and conversion of retiring thermal plant, following minimum components shall be considered:

(A) Installation of New Synchronous Condenser:

1. Synchronous Condenser
2. Generator Transformer Bank

3. Generator Circuit Breaker
4. Static Excitation System and Generator Protection System
5. Drive Motor with VFD
6. Generator Busduct
7. Generator Auxiliary System
8. MV and LV System, Air Conditioning and Miscellaneous system
9. Cabling, earthing and Lightning protection
10. EHV Bay
11. Land Cost
12. Civil Foundations and Building Cost
13. Erection, Testing and Commissioning

(B) Conversion of Retiring Thermal Plant as Synchronous Condenser (at existing location)

1. Generator Rewinding cost
2. Modification in Excitation System & Generator Protection System (if required)
3. Drive Motor with VFD
4. Generator Auxiliary System
5. Miscellaneous modifications including civil cost
6. Erection, Testing and Commissioning

6.4 Example of Possible Capacity based Cost Recovery Mechanism

A Suggestive approach for capacity based cost recovery mechanism is mentioned. One possible option for this case is that a fixed price shall be paid to the synchronous condenser based on the rating of the machine for the capability of providing the required ancillary services. Synchronous Condensers provides and absorbs reactive power as required based on its capability and is always connected to provide inertia and short circuit power in the grid without any further compensation. Penalty in case the Synchronous Condenser fails to provide any of the ancillary services as per agreement can be imposed. Payment in such a case can be made through a bilateral agreement or through an applicable tariff provision.

Another option is providing the fixed price for system inertia and short circuit power and real time pricing for reactive power based on the reactive power it actually consumes or absorbs. Real time pricing models may be the most preferred cost recovery model for installation of synchronous condenser as it can benefit the owner, regulator as well as the consumer. Difference between the two options arises because auxiliary power consumption (which is a major operational cost) reduces considerably when the synchronous condenser is in operation only for providing system inertia and short circuit power.

6.5 Regulatory Policies/Pricing Mechanism: Need of the hour

A well-planned pricing mechanism along with modifications in regulatory policies are necessary to encourage investment in installation of appropriate infrastructure for providing the required ancillary services. The policies and pricing mechanism need to be in place as early as possible for promoting investment in this area so that ancillary services providers are ready when there is a major shift from conventional generation to renewable generation.

CHAPTER-7

GLOBAL SCENARIO

7.1 Global Installations of Synchronous Condensers

The details of some of the global installations of synchronous condensers are enclosed as **Annexure-I** at the end of this chapter. Further, some global installations are elaborated below to illustrate the range of application of synchronous condenser and the support being provided by them for grid stability.

i) Installations in Demark:

Denmark has been the leading the way in installation of renewable energy and grid stabilizing equipment for smooth integration of renewables into the grid. Presently, more than 50% of generation in Denmark is from solar and wind generators.

Based on the system studies carried out by the local grid authorities, it was decided to install 7 nos. synchronous condensers at or near HVDC stations. Three of these synchronous condensers were commissioned in 2015 and are contributing to the grid stability by providing the required short circuit power and inertia.

ii) Installation for Qinghai-Henan UHVDC project:

The Qinghai-Henan UHVDC is a 1587 Km long 800KV DC line to transmit renewable energy from Qingzang Highland of Tibetan Plateau to Central China. Owned by State Grid Corporation of China (SGCC), the project is intended to deliver up to 8 GW of solar and wind power.

Due to lack of dynamic reactive power in the system and to ensure system stability, 27 Nos. of 300 MVAR synchronous condensers have been commissioned for this project.

iii) Installations in Panhandle areas of Texas:

Texas Panhandle in United States has a high wind potential and many high wind potential plants have been developed in the area. The area is situated away from large load centres and synchronous generators. System studies were carried out by the grid authorities and 2 nos. synchronous condensers were installed for improving the short circuit power. The synchronous condensers were commissioned in 2018 and as a result of these installations, there was an increase in the system strength/stability.

iv) Installations in South California, USA:

The shifting of generation mix from conventional generators to renewable generators posed challenges to the grid stability in the area. System operator after the system studies is installing 7 nos. large synchronous generators in the area for voltage regulation, inertia and short circuit power.

v) Installation with Fly Wheel in Italy:

The Italian transmission operator has tendered 16 nos. synchronous condensers with fly wheel for stabilizing the grid for short circuit power and inertia. Earlier, synchronous condensers installations have been installed and commissioned in Terna substations in Italy which have been running since end of 2015.

The flywheels along with synchronous condensers provide an additional amount of inertia for the system. 8 out of the 16 nos. installations are proposed near HVDC stations.

vi) Phoenix Hybrid STATCOM and Synchronous Condenser, UK:

This project consists of 70 MVA synchronous condenser and 70 MVA STATCOM at Scottish Power Transmission, Neilson substation. The project started test operation at end of 2020. The project aims to the demonstrate the design and operation of combined synchronous condenser and STATCOM for grid stability in view of the changing grid scenarios. The system is designed for taking advantages of both the technologies.

vii) Installations in South Australia:

The change from conventional to renewable generators has resulted in decrease in short circuit power and inertia. For increasing the system strength, 4 nos. of synchronous condensers with flywheel have already been installed in the system.

viii) Retrofit Examples:

- Two units (305 MVA and 756 MVA) conventional thermal plant at First Energy's Eastlake Plant, Ohio, USA (converted in 2013-14)
- 100 MW Gas Turbine Generator at Calpine's Cumberland Energy Centre, Millville, USA (Clutch installation, converted in 2008)
- Gas Turbine Generator at Haynes Power Station, Long Beach USA (Clutch installation, converted in 2010)
- Gas Turbine Generator at Scattergood Power Station, Playa Del Rey, USA (Clutch installation, converted in 2014)
- Two units conventional thermal plant at Brindisi Nord, Italy (converted in 2015)

7.2 Learning from Global Failures

7.2.1 South Australia Blackout (28th September 2016)

The Australian Energy Market Operator (AEMO) published a report in March 2017 for the South Australia Blackout. Brief abstracts for the sequence of events and key findings of the report are reproduced below:

Sequence of Events:

"*On Wednesday 28 September 2016, tornadoes with wind speeds in the range of 190–260 km/h occurred in areas of South Australia. Two tornadoes almost simultaneously damaged a single circuit 275 kilovolt (kV) transmission line and a double circuit 275 kV transmission line, some 170 km apart. The damage to these three transmission lines caused them to trip and a sequence of faults in* *quick succession resulted in six voltage dips on the SA grid over a two-minute period.*

As the number of faults on the transmission network grew, nine wind farms in the mid-north of SA exhibited a sustained reduction in power as a protection feature activated. For eight of these wind farms, the protection settings of their wind turbines allowed them to withstand a pre-set number of voltage dips within a two-minute period. Activation of this protection feature resulted in a significant sustained power reduction for these wind farms. A sustained generation reduction of 456 megawatts (MW) occurred over a period of less than seven seconds. The reduction in wind farm output caused a significant increase in imported power flowing through the Heywood Interconnector.

Approximately 700 milliseconds (ms) after the reduction of output from the last of the wind farms, the flow on the Victoria–SA Heywood Interconnector reached such a level that it activated a special protection scheme that tripped the interconnector offline.

The SA power system then became separated ("islanded") from the rest of the NEM (National Electricity Market). Without any substantial load shedding following the system separation, the remaining generation was much less than the connected load and unable to maintain the islanded system frequency. As a result, all supply to the SA region was lost at 4.18 pm (the Black System)"

Key Findings of the Report:

i) *"The generation mix now includes increased amounts of non-synchronous and inverter-connected plant. This generation has different characteristics to conventional plant, and uses active control systems, or complex software, to ride through disturbances. With less synchronous generation online, the system is experiencing more periods with low inertia and low available fault levels."*

ii) *"As the generation mix continues to change across the NEM, it is no longer appropriate to rely solely on synchronous generators to provide essential non-energy system services (such as voltage control, frequency control, inertia, and system strength). Instead, additional means of procuring these services must be considered, from non-synchronous generators (where it is technically feasible), or from network or non-network services (such as demand response and synchronous condensers)."*

iii) *"The technical challenges of the changing generation mix must be managed with the support of efficient and effective regulatory and market mechanisms, to ensure the most cost-effective measures are used in the long-term interest of consumers."*

7.2.2 Blackout in United States and Canada (14th August 2003)

On August 14, 2003, large portions of the Midwest and Northeast United States and Ontario, Canada, experienced an electric power blackout. The outage affected an area with an estimated 50 million people and 61,800 megawatts (MW) of electric load in the states of Ohio, Michigan, Pennsylvania, New York, Vermont, Massachusetts, Connecticut, New Jersey and the Canadian province of Ontario. A joint U.S.-Canada Power System Outage Task Force was established to investigate the causes of the blackout and ways to reduce the possibility of future outages. The report was submitted by Task Force in April 2004.

Key Findings of the Report:

Although this failure was not linked with the renewable integration, but one key point that was highlighted in the report of Task Force is that there was no monitoring and managing of the reactive power reserves for various contingency conditions. As per the report insufficient reactive power/voltage balance was the cause of the blackout.

This highlights the requirement of reactive power reserves for maintaining the grid stability in contingency situations.

Annexure-I

Table-4: List of Global Synchronous Condenser Installations

S. No.	Country	Location/ Project	Inertia constant MWs/ MVA	Kinetic Energy in MWs	Type of Machine Cylindrical/ salient pole	Rating		
						MVAR delivery	MVAR absorption	S.C. Support (MVA)
1.	Ireland	Moneypoint		4000	cylindrical	245	-111	830
2.	Estonia	Kiisa		1750	cylindrical	50	-50	900
3.	Estonia	Viru		1750	cylindrical	50	-50	900
4.	Estonia	Püssi		1750	cylindrical	50	-50	900
5.	United Kingdom	Grain		2 x 1700	cylindrical	2 x 115	-90	570
6.	United Kingdom	Scottish Power				70		
7.	Italy	Rosara		1780	cylindrical	250	-125	1100
8.	Germany	Hoheneck		610	cylindrical	430	-260	1200
9.	Germany	Ampirion GmbH				330		
10.	Germany	Tenne TSO				250		
11.	Germany	Oberottmarshausen		610	cylindrical	300	-200	1200
12.	United Kingdom	Rassau		1100	cylindrical	60	-60	420
13.	United Kingdom	STATKRAFT				67		
14.	Italy	Fano		1780	cylindrical	250	-125	1100
15.	Australia	Robertstown		1100	cylindrical	125	-70	580
16.	Australia	KIAMAL Solar Farm		340	cylindrical	190	-70	730
17.	Australia	Davenport				2*129		
18.	Australia	Darlington point solar farm				42		
19.	Australia	Silverton wind farm				40		
20.	Australia	Haughton solar farm Pacific Hydro				65		
21.	Australia	South Australia	8.53	2 x 1100	Cylindrical / 3000	2 x 129	2 x -77	2 x 642
22.	USA	Blackwater		470	cylindrical	158	-114	960
23.	USA	Alibates		470	cylindrical	160	-70	950
24.	USA	Tule Canyon		470	Cylindrical	160	-70	950
25.	USA	Songs Mesa		470	Cylindrical	225	-120	970
26.	USA	Miguel		2x470	Cylindrical	450	- 225	970
27.	USA	San Luis Rey		470	Cylindrical	225	-120	970
28.	USA	Talega		470	Cylindrical	225	-120	970
29.	USA	Fieldale				2*100		
30.	USA	Eversource Stony Hill				25		
31.	USA	Santiago Southern California Edison				3*81		
32.	USA	Eversource Saco Valley				2*25		
33.	USA	Blue sky West Bingham				60		
34.	USA	Standpipe Pacific Corp				65		

S. No.	Country	Location/Project name	Inertia constant MWs/ MVA	Kinetic Energy in MWs	Type of Machine Cylindrical/salient pole	Rating		
						MVAR delivery	MVAR absorption	S.C. Support
35.	USA	Oakfield Blue Sky East				60		
36.	USA	Vermont	1.73	4 x 43	Salient Pole /	4 x 25	4 x -12.5	4 x 131
37.	USA	Midwest				560	-310	
38.	USA	Finlay Solar Park				60		
39.	USA	Panhandle Texas				2*175	-125	
40.	USA	Maine – 1	1.95	117	Salient Pole / 1800	60	-27	350
41.	USA	Maine – 2	1.95	117	Salient Pole / 1800	60	-27	350
42.	USA	Wyoming	1.84	120	Salient Pole / 1200	65	-40	310
43.	USA	California	1.46	3 x 118	Salient Pole / 1200	3 x 81	3 x -35	3 x 324
44.	USA	New Hampshire – 1	1.49	2 x 37	Salient Pole / 1800	2 x 25	2 x -12.5	2 x 97
45.	USA	Connecticut	1.49	37	Salient Pole /1800	25	-12.5	98
46.	USA	New Hampshire – 2	1.49	2 x 37	Salient Pole / 1800	2 x 25	2 x -12.5	2 x 97
47.	USA	Virginia – 1	1.39	2 x 139	Salient Pole / 1200	2 x 100	2 x -50	2 x 342
48.	USA	Virginia – 2	1.39	2 x 139	Salient Pole / 1200	2 x 100	2 x -50	2 x 342
49.	USA	Maine – 1	1.95	117	Salient Pole / 1800	60	-27	350
50.	Korea	Jeju Island	1.93	2 x 97	Salient Pole / 1800	2 x 50	2 x -25	2 x 224
51.	Norway	Feda		340	cylindrical	170	-90	740
52.	Denmark	Herslev		450	cylindrical	200	-120	1000
53.	Denmark	Fraugde		450	cylindrical	200	-120	1000
54.	Denmark	Bjaeverskov		450	cylindrical	270	-140	900
55.	Georgia	Black Sea		80	cylindrical	60	-39	250
56.	Italy	ICS Matera	7.08	1770	Cylindrical	250	-125	1198
57.	Italy	ICS Matera	7.08	1770	Cylindrical	250	-125	1198
58.	Italy	ICS Codrongianos	1.69	423	Cylindrical	250	-125	1277
59.	Italy	ICS Codrongianos	1.69	423	Cylindrical	250	-125	1277
60.	Italy	ICS Codrongianos	7.08	1770	Cylindrical	250	-125	1198
61.	Italy	ICS Foggia	7.08	1770	Cylindrical	250	-125	1198
62.	Italy	ICS Garigliano	7.08	1770	Cylindrical	250	-125	1198
63.	Italy	ICS Villanova	7.08	1770	Cylindrical	250	-125	1198
64.	Italy	ICS Candia	7.08	1770	Cylindrical	250	-125	1198
65.	Italy	Maida				2*250		
66.	Italy	Salargius				2*250		
67.	Italy	Brindisi				2*250		
68.	Italy	Brindisi Nord	7.08	1770	Cylindrical	250	-125	Retrofit
69.	Italy	Brindisi Nord	7.08	1770	Cylindrical	250	-125	Retrofit
70.	Italy	Partinico				170		
71.	Italy	Favara				170		
71.	Canada	Winnipeg, Dorsey Inverter station of BPI HVDC Bipole	1.41	226.4	Salient Pole	160	-80	0.653 (SCR)

S. No.	Country	Location/Project name	Inertia constant MWs/MVA	Kinetic Energy in MWs	Type of Machine Cylindrical/salient pole (r.p.m.)	Rating		
						MVAR delivery	**MVAR absorption**	**S.C. Support**
72.	Canada	Winnipeg, Dorsey Inverter station of BPI HVDC Bipole	1.99	318.09	Salient Pole	160	-80	0.653 (SCR)
73.	Canada	Winnipeg, Dorsey Inverter station of BPII HVDC Bipole	2.2	660.0	Salient Pole	300	-165	0.653 (SCR)
74.	Canada	Winnipeg, Riel Inverter station of BPIII HVDC Bipole	2.5	625.0	Salient Pole	4*250	-125	0.653 (SCR)
75.	Canada	Hydro Quebec Copper Mountain				25		
76.	Canada	Hydro Quebec Cadillac				25		
77.	Canada	Rainbow Lake				50		
78.								
79.	China	Zhalute 2				27*300	-150	
80.	China	Jiuquan 2					-150	
81.	China	Xuming Substation (5 SynCons)					-150	
82.	China	Huaian 2					-150	
83.	China	Ziangtan 2					-150	
84.	China	Ximeng 2					-150	
85.	China	Taizhou 2					-150	
86.	China	Guquan 2					-150	
87.	UK	Rassau		750	Salient Pole	60	-60	-
88.	UK	Keith		450	Salient Pole	2*65	-57	-
89.	UK	Lister Drive		450	Salient Pole	2*65	-57	-
90.	Australia	Tasmania	4.1	656	Salient Pole (273)	70	-72	
91.	Australia	Tasmania	3.57	571	Salient Pole (273)	70	-61	
92.	Australia	Tasmania	3.65	496	Salient Pole (167)	72	-74	
93.	Australia	Tasmania	3.15	356	Salient Pole (200)	49	-44	
94.	Australia	Tasmania	3.72	350	Salient Pole (167)	50	-42	
95.	Australia	Tasmania	3.7	348	Salient Pole (167)	40	46	
96.	Australia	Tasmania	4.2	282	Salient Pole (600)	40	20	
97.	Australia	Tasmania	3.1	149	Salient Pole (500)	21	17	
98.	Australia	Tasmania				14		
99.	Netherlands	Rotterdam/Maasvlakte MPP2	10.5	500/625	Cylindrical	280	-280	

CHAPTER-8

CASE STUDY (SIMULATION)

8.1 Simulation study

In order to study the impact of synchronous condensers on grid stability, few simulations were carried out by NTPC. The simulation studies have been carried out using PSSE software on IEEE 14 bus system. The simulation studies have been carried out for studying the impact of addition of renewable generators, withdrawal of conventional generators and addition of synchronous generators in a RE dominant network. Further, simulations have been carried out for voltage response/dynamic reactive power capabilities of various available technologies such as SVC, STATCOM and synchronous condensers during the fault condition. Network of IEEE 14 bus system considered for simulation studies is given in the figure below:

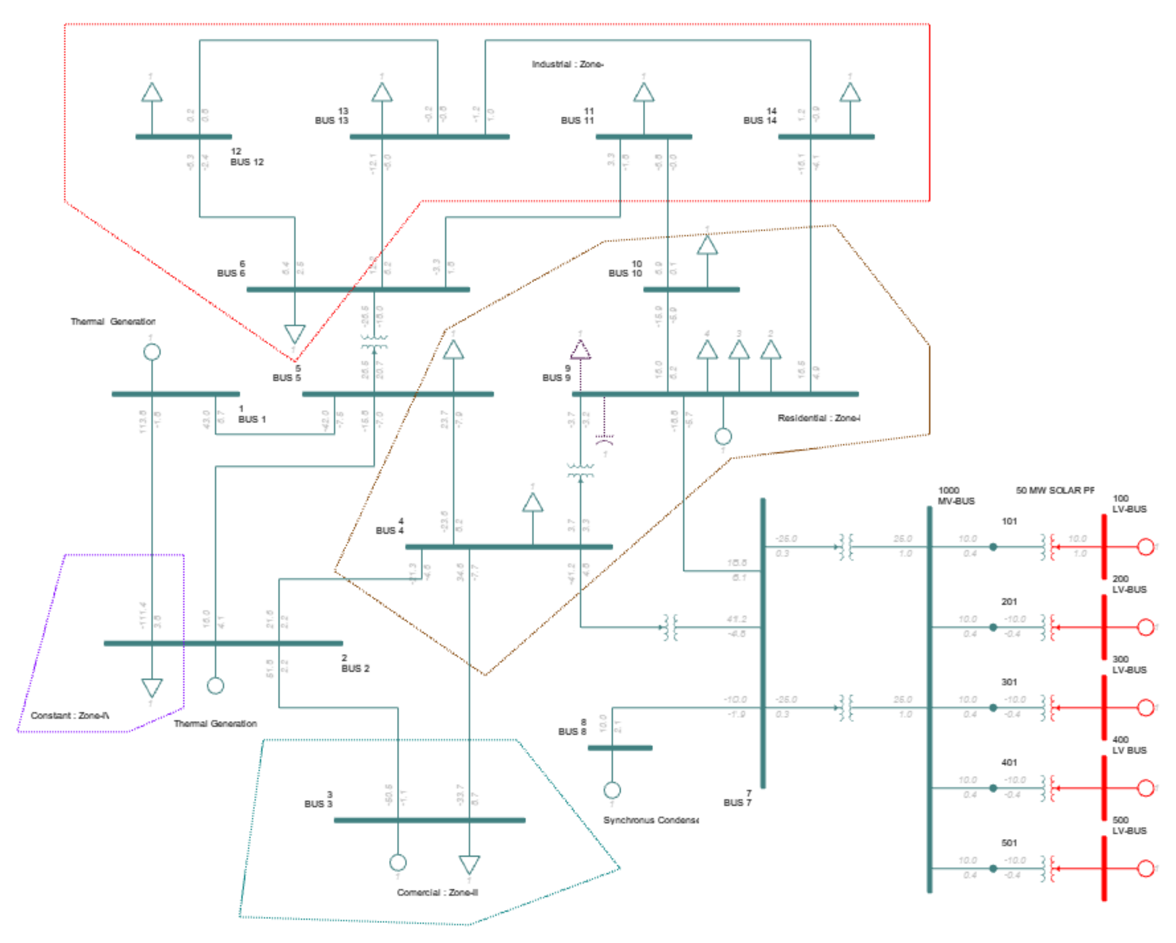
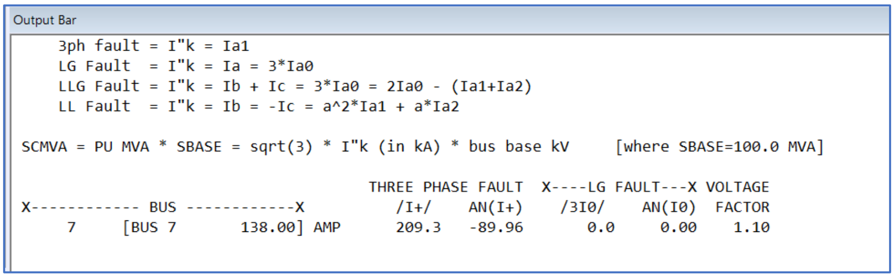


Figure 16: IEEE 14 Bus Network Considered for Simulation Studies

The network consists of 5 nos. RE generators of capacity 10 MW each connected in the system at 132 KV level of Bus-7 . Further, conventional generators have been connected in the system on Bus No. 1, 2, 3, 8 & 9.. Synchronous condenser has been connected in the system on Bus No. 8 and 9. The generation provided by these conventional generators are mentioned in the respective case studies.

A) Simulations for Short Circuit Ratio (SCR)

Case-1: No conventional generation/synchronous condensers are connected in the system (all RE generators connected): For case-1, no conventional generators and synchronous condensers are connected in the system. All the RE generators (50 MW) are connected. The simulation results for this case are given in the figure below:



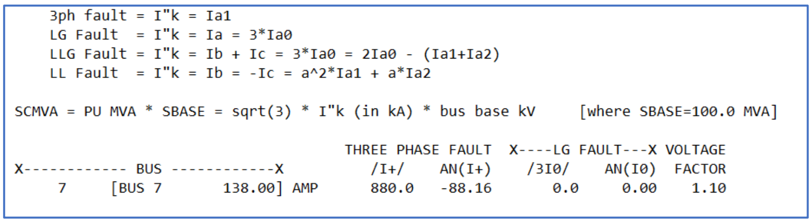
```
    3ph fault = I"k = Ia1
    LG Fault  = I"k = Ia = 3*Ia0
    LLG Fault = I"k = Ib + Ic = 3*Ia0 = 2Ia0 - (Ia1+Ia2)
    LL Fault  = I"k = Ib = -Ic = a^2*Ia1 + a*Ia2

SCMVA = PU MVA * SBASE = sqrt(3) * I"k (in kA) * bus base kV     [where SBASE=100.0 MVA]

                                      THREE PHASE FAULT  X----LG FAULT---X VOLTAGE
X------------ BUS ------------X          /I+/    AN(I+)    /3I0/    AN(I0)  FACTOR
     7     [BUS 7       138.00] AMP      209.3   -89.96       0.0     0.00    1.10
```

Figure 17: Simulation Results for Short Circuit Ratio (Case-I)

Short Circuit Ratio calculated at Bus-7 in the above case is 0.96.

Case-2: Conventional generation (150 MW) + RE generation (50 MW) in the system and no synchronous condensers are connected:

One conventional generator is connected on Bus-1 and is feeding 150 MW into the system. RE generators are feeding 50 MW in system. The simulation results for this case are given in the figure below:



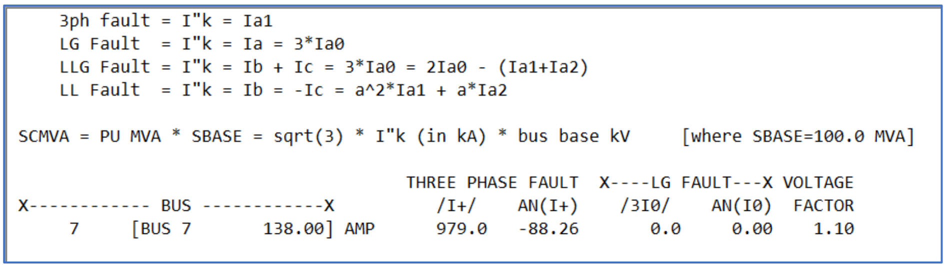
```
    3ph fault = I"k = Ia1
    LG Fault  = I"k = Ia = 3*Ia0
    LLG Fault = I"k = Ib + Ic = 3*Ia0 = 2Ia0 - (Ia1+Ia2)
    LL Fault  = I"k = Ib = -Ic = a^2*Ia1 + a*Ia2

SCMVA = PU MVA * SBASE = sqrt(3) * I"k (in kA) * bus base kV     [where SBASE=100.0 MVA]

                                      THREE PHASE FAULT  X----LG FAULT---X VOLTAGE
X------------ BUS ------------X          /I+/    AN(I+)    /3I0/    AN(I0)  FACTOR
     7     [BUS 7       138.00] AMP      880.0   -88.16       0.0     0.00    1.10
```

Figure 18: Simulation Results for Short Circuit Ratio (Case-2)

Short Circuit Ratio calculated at Bus-7 in the above case is 4.02.

Case-3: Conventional generation (250 MW) + RE generation (50 MW) in the system and no synchronous condensers are connected:

All conventional generators are connected in the system and feeding total of 250 MW. RE generators are feeding 50 MW in system. The simulation results for this case are given in the figure below:



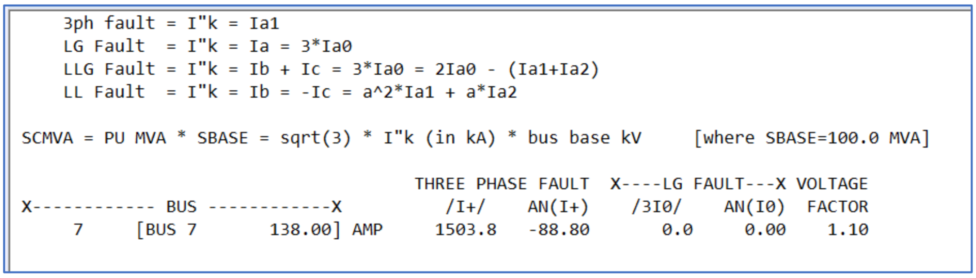
```
     3ph fault = I"k = Ia1
     LG Fault  = I"k = Ia = 3*Ia0
     LLG Fault = I"k = Ib + Ic = 3*Ia0 = 2Ia0 - (Ia1+Ia2)
     LL Fault  = I"k = Ib = -Ic = a^2*Ia1 + a*Ia2

SCMVA = PU MVA * SBASE = sqrt(3) * I"k (in kA) * bus base kV     [where SBASE=100.0 MVA]

                                      THREE PHASE FAULT  X----LG FAULT---X VOLTAGE
X------------ BUS ------------X          /I+/     AN(I+)    /3I0/     AN(I0)  FACTOR
     7     [BUS 7       138.00] AMP      979.0    -88.26       0.0      0.00    1.10
```

Figure 19: Simulation Results for Short Circuit Ratio (Case-3)

Short Circuit Ratio calculated at Bus-7 in the above case is 4.47.

Case-4: Conventional generation (250 MW) + RE generation (50 MW) + Synchronous Condenser (50 MVAR) connected in the system:

All conventional generators are connected in the system and are feeding 250 MW. RE generators are feeding 50 MW in system. Further, in this case one synchronous condenser (50 MVAR) is also connected in the system on Bus-8. The simulation results for this case are given in the figure below:



```
     3ph fault = I"k = Ia1
     LG Fault  = I"k = Ia = 3*Ia0
     LLG Fault = I"k = Ib + Ic = 3*Ia0 = 2Ia0 - (Ia1+Ia2)
     LL Fault  = I"k = Ib = -Ic = a^2*Ia1 + a*Ia2

SCMVA = PU MVA * SBASE = sqrt(3) * I"k (in kA) * bus base kV     [where SBASE=100.0 MVA]

                                      THREE PHASE FAULT  X----LG FAULT---X VOLTAGE
X------------ BUS ------------X          /I+/     AN(I+)    /3I0/     AN(I0)  FACTOR
     7     [BUS 7       138.00] AMP     1503.8    -88.80       0.0      0.00    1.10
```

Figure 20: Simulation Results for Short Circuit Ratio (Case-4)

Short Circuit Ratio calculated at Bus-7 in the above case is 6.88.

From the above simulation studies, it can be concluded that Short Circuit Ratio is expected to decrease in systems/areas with high renewable penetration and no conventional generation in the near vicinity. It can be seen from the simulation studies that synchronous condensers can increase the short circuit ratio by providing the required short circuit power in system during fault conditions. Hence, augmentation of RE rich networks with synchronous condensers can be one of the best possible solutions for providing the short circuit power during fault conditions and can therefore help in maintaining the system stability.

B) Simulations for Dynamic Reactive Power

Following cases have been considered for simulation studies of dynamic reactive power and system response (fault has been considered on Bus-5):

- **Case-1: All RE generators are connected in the system (no conventional generation, no compensation device is connected)**
- **Case-2: All RE generators connected in the system and SVC connected on Bus-9**
- **Case-3: All RE generators connected in the system and STATCOM connected on Bus-9**
- **Case-4: All RE generators connected in the system and Synchronous condenser connected on Bus-9**

The simulation study results for voltage profile/dynamic reactive ability of different cases are given below:

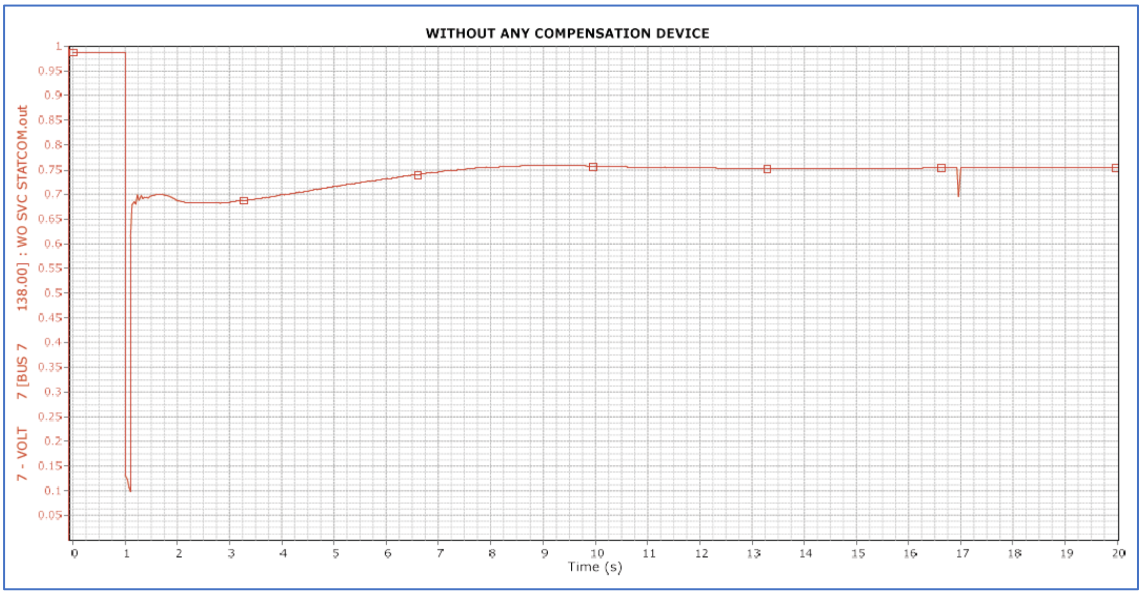


Figure 21: Simulation Results for Dynamic Reactive Power Capability (Case-1)

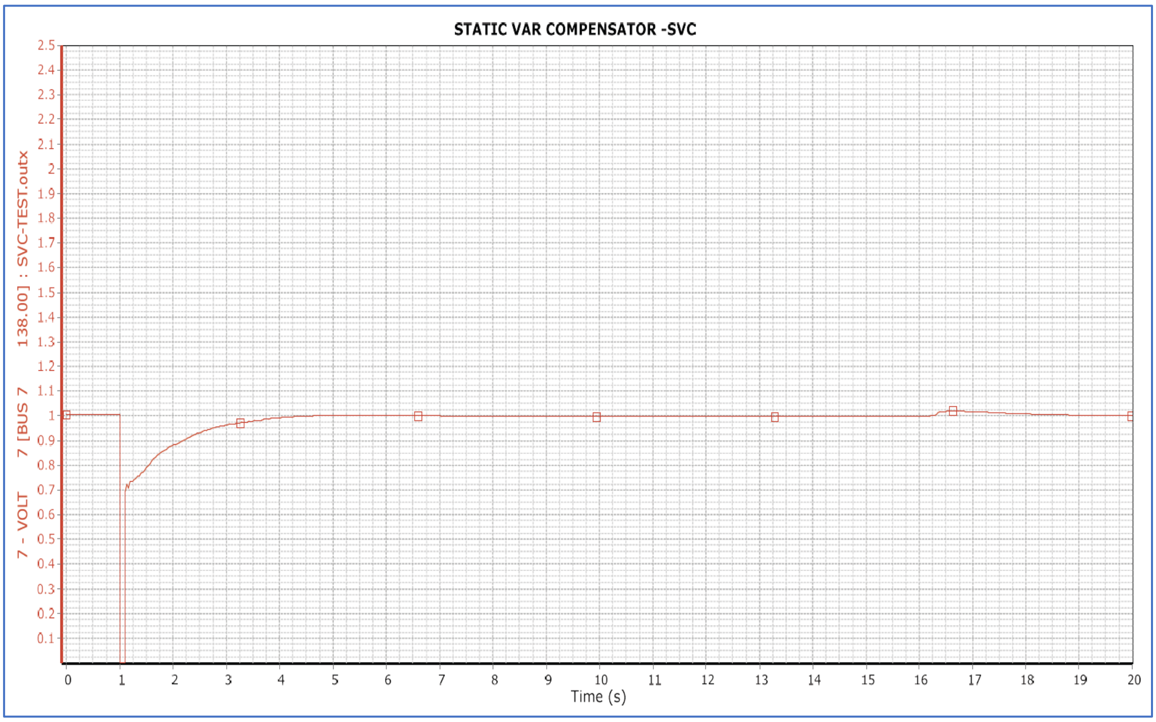


Figure 22: Simulation Results for Dynamic Reactive Power Capability (Case-2)

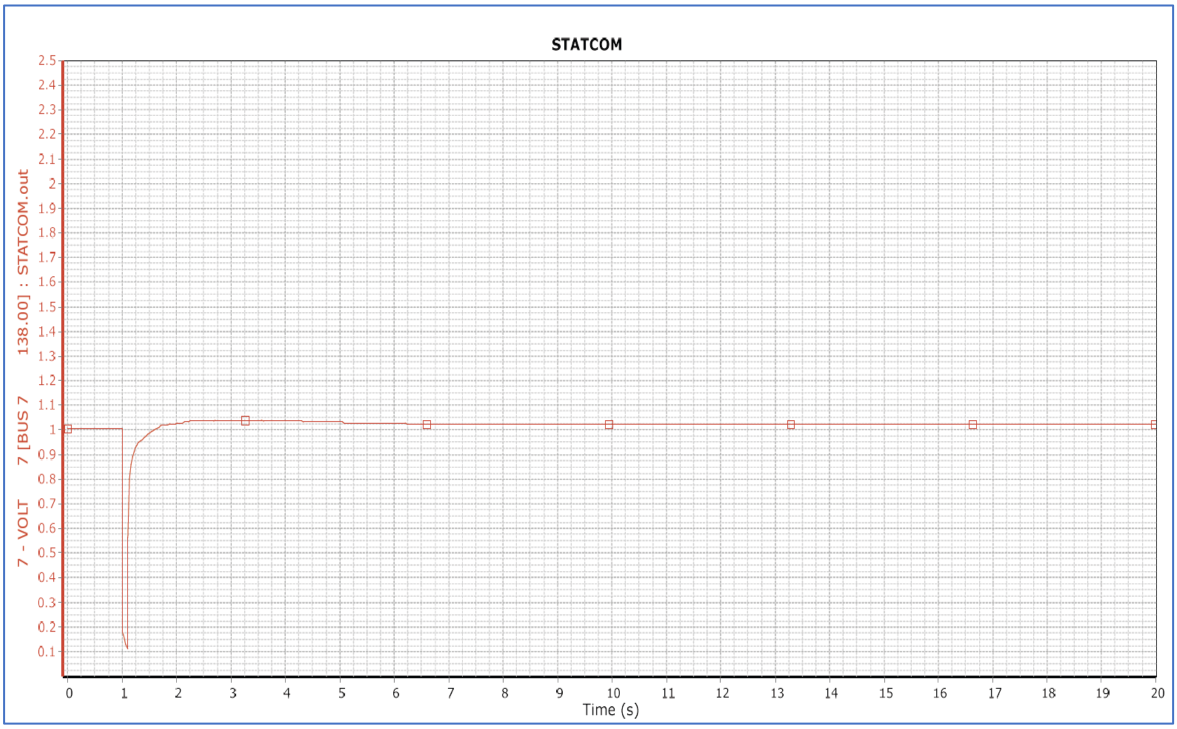


Figure 23: Simulation Results for Dynamic Reactive Power Capability (Case-3)

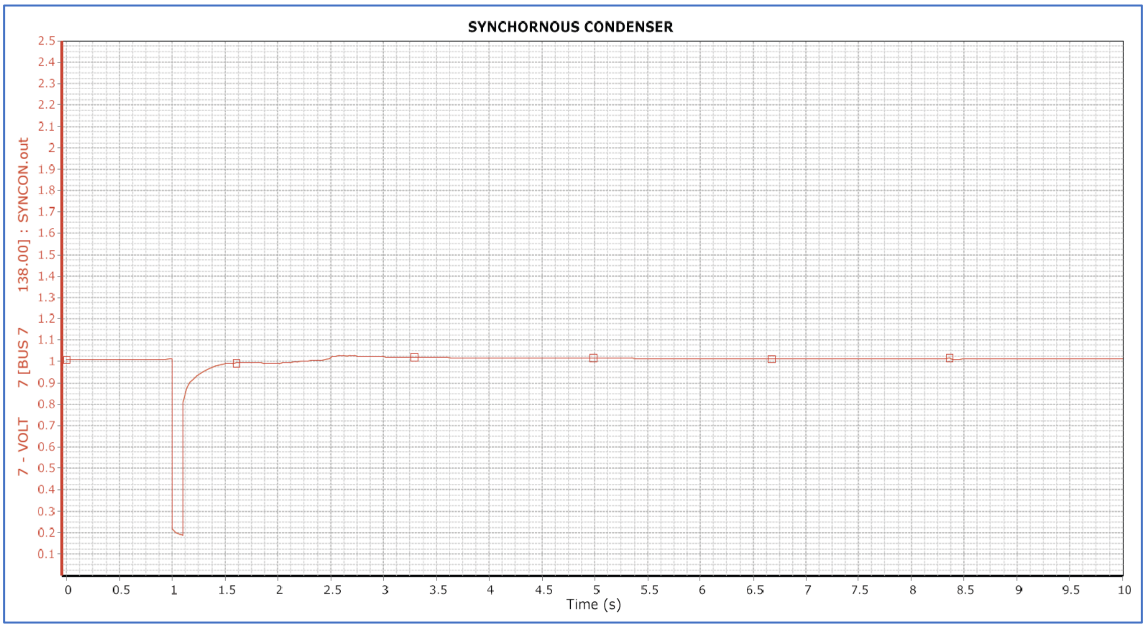
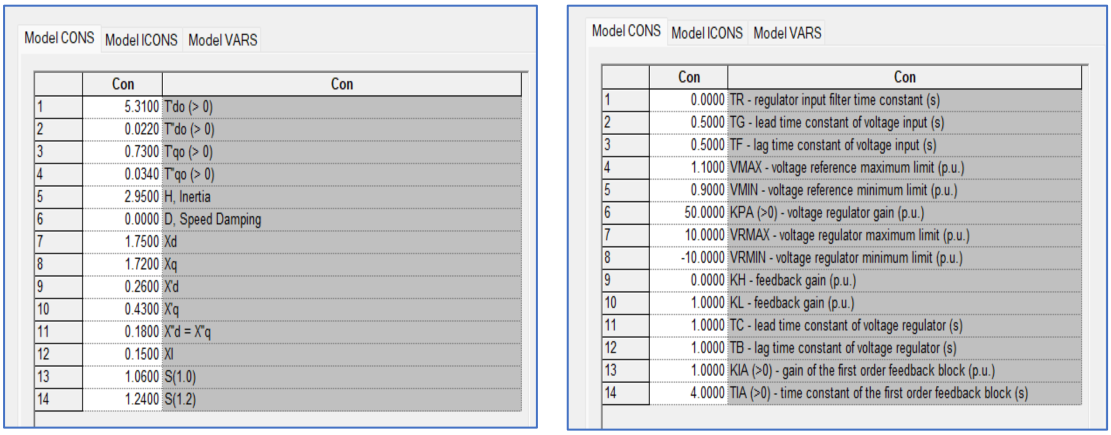


Figure 24: Simulation Results for Dynamic Reactive Power Capability (Case-4)

The parameters/models for synchronous condenser (excitation and machine parameters) used in the simulation study are given below:



	Con	Con
1	5.3100	T'do (> 0)
2	0.0220	T"do (> 0)
3	0.7300	T'qo (> 0)
4	0.0340	T"qo (> 0)
5	2.9500	H, Inertia
6	0.0000	D, Speed Damping
7	1.7500	Xd
8	1.7200	Xq
9	0.2600	X'd
10	0.4300	X'q
11	0.1800	X"d = X"q
12	0.1500	Xl
13	1.0600	S(1.0)
14	1.2400	S(1.2)

	Con	Con
1	0.0000	TR - regulator input filter time constant (s)
2	0.5000	TG - lead time constant of voltage input (s)
3	0.5000	TF - lag time constant of voltage input (s)
4	1.1000	VMAX - voltage reference maximum limit (p.u.)
5	0.9000	VMIN - voltage reference minimum limit (p.u.)
6	50.0000	KPA (>0) - voltage regulator gain (p.u.)
7	10.0000	VRMAX - voltage regulator maximum limit (p.u.)
8	-10.0000	VRMIN - voltage regulator minimum limit (p.u.)
9	0.0000	KH - feedback gain (p.u.)
10	1.0000	KL - feedback gain (p.u.)
11	1.0000	TC - lead time constant of voltage regulator (s)
12	1.0000	TB - lag time constant of voltage regulator (s)
13	1.0000	KIA (>0) - gain of the first order feedback block (p.u.)
14	4.0000	TIA (>0) - time constant of the first order feedback block (s)

Figure 25: Synchronous Condenser Model used for Simulation Study

From the above simulation studies, it is observed that both STATCOMs and synchronous condensers can provide fast response to provide dynamic reactive power into the system as per requirement. The response of STATCOM is slightly better than synchronous condensers. However, synchronous condensers can provide other ancillary benefits of inertia and short circuit power apart from a considerable fast response for dynamic reactive power.

Efforts were carried out to capture frequency response and inertia constant using different compensation devices for various scenarios on IEEE-14 bus system. However, due to limited network of IEEE-14 bus system and availability of proper frequency trend, accurate results could not be obtained for inertia/frequency response. Accordingly, it was concluded that Electromagnetic Transient (EMT) simulation software like PSCAD/EMTP might represent these dynamic characteristics accurately compared to RMS simulation software like PSSE. Therefore, to ensure the highest level of accuracy, the report excludes the analysis/simulation studies for frequency response and inertia constant of the system. Further, similar detailed modelling in EMT tools is recommended for validating the dynamic response of synthetic inertia sources like BESS and E-STATCOM, rather than relying on RMS simulation tools.

The simulation studies need to be carried out on the actual network files of Indian Power system considering the planned RE integration, to ascertain the areas requiring strengthening of short circuit power and dynamic reactive power reserves. Further, inertia mapping for the grid with planned RE integration also needs to be carried out. Based on ancillary service requirement worked out in these studies, appropriate compensation devices/systems need to be installed at the strategic locations to ensure grid stability in future. Further, pilot installation (if not installed earlier) of each type of compensation device may be carried out in India to understand the ground performance on these devices in the Indian Power System scenario.

CHAPTER-9

NTPC Role for Synchronous Condenser Installations

9.1 NTPC Internal Targets

NTPC has committed to install 60 GW of renewable energy capacity by 2032. Further, NTPC targets a market share of 25% in ancillary services and storage. With GoI target of 500 GW of non-fossil fuel-based capacity by 2030, there will be significant requirement of short circuit power, inertia and dynamic reactive power support for grid stability. Synchronous condensers can be one of the most suitable solutions for provision of these ancillary services. Considering extensive experience of NTPC with synchronous machines, NTPC can play a vital role for installation/O&M of the synchronous condenser installations based on the requirements provided by the system operator. Further, NTPC is committed to ensure reliability and stability of the Power System and has already been providing active/reactive power support to the grid from its conventional generators as per the requirements given by the system operators.

9.2 Works carried out by NTPC

i) Studies on Synchronous Condensers: NTPC has carried out simulation studies on sample networks to illustrate the challenges of grid stability with the integration of renewable energy sources. The impact of using different available solutions on some of the ancillary services have been worked out. Further, studies have been done for re-purposing of the retiring assets as synchronous condensers which include modifications required, challenges for re-purposing, advantages of using new synchronous condensers, auxiliary requirements, layout, system sizing etc. Also, technical requirements for installation of a new synchronous condenser installation have been studied by NTPC.

ii) Site visit to Jam Khambaliya Pooling Station: Site visit to Jam Khambaliya Pooling station was carried out by NTPC representative. CTU/CEA had intimated NTPC to explore the possibility of re-purposing Talcher generator as synchronous condenser at Jam Khambaliya Pooling Station in Gujarat (transportation to new site). After site visit, it was concluded that re-purposing of Talcher Generator at a new location shall not be a feasible option due to land, water constraints and transportation challenges.

iii) Discussion with various stakeholders: NTPC has made several deliberations to CEA/CTU/Grid India on the future challenges of grid stability with the planned RE integration and withdrawal of conventional energy sources from the grid. Also, discussions have been carried out with various OEMs on technology aspects/advancements in new synchronous installations, modalities & challenges for re-purposing generators of existing coal and gas power plants etc.

iv) Discussion with Gas Turbine (GT) OEMs for provision of clutch arrangement: NTPC has carried out several discussions with GT OEMs for exploring the possibility of providing clutch arrangement in the existing gas plants of NTPC.

9.3 NTPC Experience in Synchronous Machines/Role for Synchronous Condenser Installation:

i) Experience of Design/Erection/Commissioning: NTPC has extensive experience of engineering, installation, erection, testing and commissioning of synchronous machines. The design, installation, testing and commissioning of synchronous condensers is similar to the synchronous generators. This experience of NTPC can help in smooth installation of these machines without any challenges. Further, engineering, finalization of technical specifications of synchronous condensers can be done by NTPC based on the requirements provided by the system operator.

ii) Experience of O&M: NTPC has rich experience of O&M of synchronous machines and has consistent track record of high availability and Plant Load Factor (PLF) across plants based on the diverse technologies. NTPC has systems and knowledge for predictive and preventive maintenance systems to achieve the required PLF, which shall be a very important aspect for synchronous condenser installations/grid stability. NTPC can utilize this experience and provide the O&M services (as per the agreed modalities) for synchronous condenser installations, which otherwise will have to be taken care by the system operators.

iii) Experience of System Integration: Many OEMs for synchronous condensers are available in India. However, some of the OEMs can only provide synchronous condensers may not be able to provide a complete plant EPC solution (i.e., may not include civil works, Step-up transformer, Isolated Phase Bus Duct etc). NTPC has the experience of integration of various systems in the power plant and can prepare the tender documents/ specifications accordingly. Further, smooth integration of all the systems for complete plant turnkey/package concept can be done by NTPC. This will ensure equal opportunity to all OEMs for participation in the tender for synchronous condenser installation.

iv) Existing Gas Plants for Conversion as Synchronous Condensers: NTPC has existing gas power plants located near load centres. The feasibility study for provision of clutch arrangement in existing gas turbines of NTPC can be done if suitability (as per system requirement) is confirmed by system operator. However, modalities for recovery of capital and operational cost need to be finalized before such modifications/feasibility studies are taken up.

9.4 Possible Business Models (for installation of synchronous condenser by NTPC):

Installation based on ROE/Annual Fixed Cost Payment Model: In this model, NTPC may install the synchronous condenser on behalf of transmission utility. Annual Fixed costs (ROE, O&M expenses, Interest on loan, depreciation etc.) shall be reimbursed by transmission utility to NTPC. Further, the active power cost for running of synchronous condensers shall be borne by transmission utility/system operator or shall be included in the losses. The transmission utility shall have an advantage in this model as they do not have to pay upfront cost for installation of the equipment in this case (as is presently being done for other compensation devices being installed). Based on the modalities finalized, O&M services can also be done by NTPC in this case, which shall also be an advantage to the transmission utility/system operator.

The modalities of annual fixed cost need to be finalized in this case. Further, it is expected that synchronous condenser installations shall be in/near the pooling stations. In such a case, land for installation of synchronous condenser needs to be provided by CTU/PGCIL. The modalities for land ownership also need to be finalized in this case.

Considering the extensive experience of NTPC in the field of synchronous machines and the studies already carried out for synchronous condensers, NTPC can play an important role for synchronous condenser installations in the country. System studies need to be carried out to ascertain the location and type of ancillary service/compensation device required at a particular location.

CHAPTER-10

CONCLUSION

The increasing penetration of renewable energy into the grid poses many challenges to the stability and reliability of the power system. The most important parameters for ensuring the system stability and reliability with integration of renewable energy in the grid are system inertia, short circuit power and fast reactive power response. These ancillary services have inherently been provided by the conventional generators and therefore grid stability due to these ancillary services has never been a challenge in the pre-renewable era. Renewable energy generators do not contribute to inertia as they are connected to the grid through power electronic devices, have limitations in providing short circuit power and dynamic reactive power. Therefore, in renewable rich network, necessary compensation devices need to be installed at strategic locations for providing solutions to the challenges of these ancillary services for ensuring grid stability and reliability.

There are many solutions which are available in the market for the provision of these ancillary services. Some of these solutions are already installed by system operators globally. However, these available solutions have certain advantages and some limitations for providing different ancillary services. Therefore, it becomes imperative to identify the required ancillary service at a particular location and accordingly install the appropriate compensation devices. For identifying the required ancillary service, system studies need to be carried out by the system operator. Based on these system studies, type of ancillary service, its specification and accordingly compensation devices need to be selected.

Considering the effectiveness of synchronous condensers to provide inertia, system strength including transient capability to supply short circuit current and high reactive power support, synchronous condensers emerge as one of the strongest technical solutions to deal with the grid stability issues with renewable integration. There are two possible solutions for installation of synchronous condenser i.e., conversion of existing generator of fossil-fuel based plants (which are synchronous machines) as Synchronous Condenser or installing a new synchronous condenser. There are many challenges/life cycle costs which need to be assessed for re-purposing retiring assets such as remaining life, re-winding of generator, system requirements, conversion costs, commercial arrangements with the plant owners, guarantee/warranty of the old system, transportation challenges (OEM works for re-winding and back or a new location) and land, water availability & land cost etc. for relocation to a new area. On the other hand, new synchronous condensers can be tailored made as per system requirement, require lesser auxiliaries, have comparatively lesser footprint, require less quantity of water, have higher life expectancy etc. Further, CEA has advised that no retirement or re-purposing of coal-based power stations (greater than 200 MW) will be done before 2030. Therefore, it is more advisable to go for installation of new synchronous condensers based on the system requirements.

NTPC is targeting a renewable energy generation of 60 GW and market share of 25% in ancillary services and storage by 2032. Further, considering the extensive experience of NTPC in engineering, integration and O&M of synchronous machines, NTPC can play an important role for synchronous condenser installations in the country. NTPC also has systems and knowledge for predictive and preventive maintenance systems to achieve the required PLF, which shall be a very important aspect for synchronous condenser installations/grid stability. Also, NTPC is pro-actively working for identifying the systems/modifications/ specifications required for retrofit/new synchronous condenser installations. Further NTPC has access to few simulation softwares required for such simulation studies. Also, simulation studies on IEEE 14 bus system have been carried out by NTPC to demonstrate the impact of renewable integration and performance of some of the available solutions for addressing these challenges.

System studies for the type of ancillary service required, its specification, identification of location for installation of these devices along with pricing mechanism and regulatory policies for compensation is necessary for promoting investment in these ancillary services. These systems need to be in place as early as possible so that ancillary service providers are ready when there is a major shift from conventional to renewable generation. Further, pilot installation (if not installed earlier) of each type of compensation device may be carried out in India to understand the ground performance of these devices in the Indian Power System scenario.

Augmentation of the system with appropriate compensation devices, can make the grid performance at par with conventional power generation technologies, where active power is being generated from wind farms or solar parks and other requirements like system inertia, short circuit withstand capability, dynamic voltage support etc. are met by these devices.

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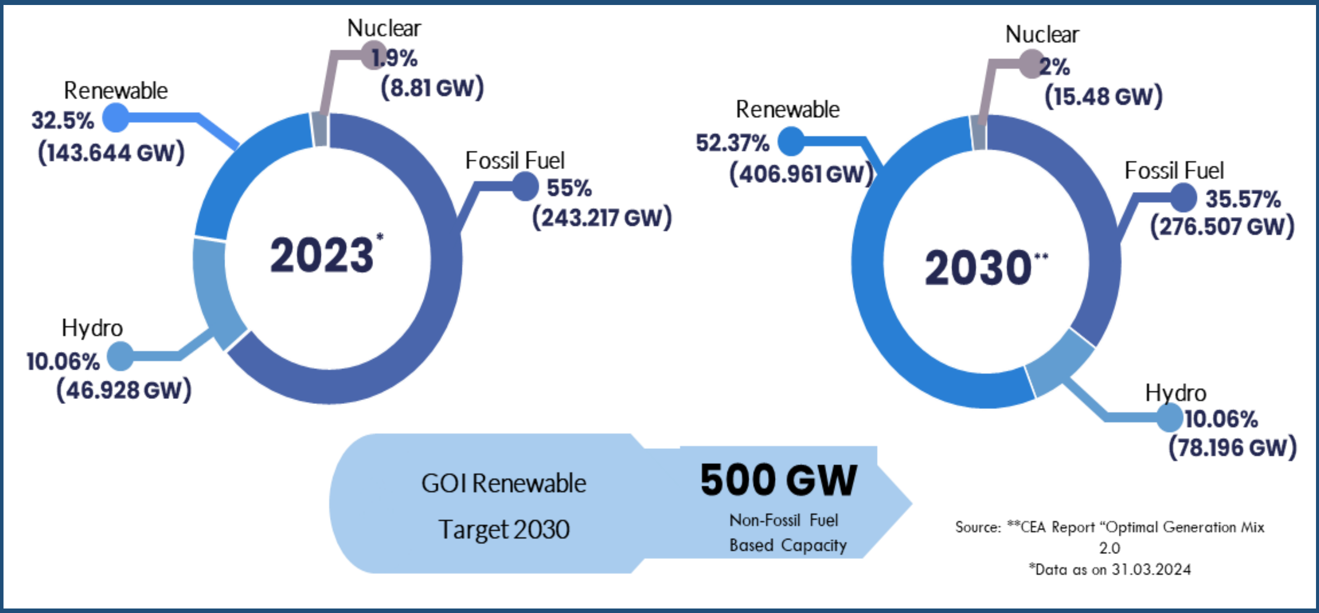
Synchronous Condenser

Strongest grid stability solution for clean energy transformation



Source: **CEA Report "Optimal Generation Mix 2.0
*Data as on 31.03.2024

DRIVERS:
- Renewable Integration
- Grid Stability

RESTRAINT:
- Regulations for ancillary services
- Cost Recovery Models

OPPORTUNITY:
- NTPC ancillary services target
- Strongest technical solution

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