Exploring the Enhanced Performance of a Static Synchronous Compensator with a Super-Capacitor in Power Networks

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Received: 7 September 2022 | Revised: 27 September 2022 | Accepted: 29 September 2022

Abstract-The use of a super-capacitor as a storage device integrated with a Voltage source converter-based shunt-connected Static Synchronous Compensator (STATCOM) is proposed for improving the STATCOM performance during sudden large disturbances in a power network. The super-capacitor was applied across the STATCOM capacitor during the disturbance condition. MATLAB simulations were carried out for the verification of a secondary function of the STATCOM like oscillation damping, transient stability improvement, and security of the power network with the storage device. The validation of the proposed super-capacitor was carried out in MATLAB.

Keywords-STATCOM; storage device; super-capacitor; transient stability; security

I. INTRODUCTION

Power demand is increasing in comparison to power production. To balance it, enlargement or modification of the power network is needed, which results in complex design and unsecure operation of the network. With this complex design, the network becomes very sensitive to various types of disturbance like faults, line switching, contingency, congestion, etc., leading to a decline in stability, security, and reliability of the power network [1-2]. Power network stability plays a very imperative role in securing the network operation. The instability in power network exhibits itself in various ways, such as frequency, angle, and speed deviations, and power and voltage oscillations. Power network stability status may be steady state, transient state, or dynamic. Transient stability is mainly affected by major disturbances. Proper power network devices are used to enhance stability and to increase security. Shunt-connected voltage source converter-based reactive power compensation devices are widely adopted to overcome voltage stability issues. However, to compensate the true power in the network, Super-Capacitors (SCs) with the additional benefit of storage are used [3-4].

In [5], a supplementary HVDC technology for STATCOM is considered for steady state and transient stability characteristics. In [6], a battery energy storage system was taken as a package of storing elements and VSC to provide autonomous control of the active and reactive power injection to the grid. In [7], the transient stability margin of a power network connected STATCOM is determined using trajectory sensitivity analysis. A SC type energy storage system is used to enhance the transient state stability analysis of a grid connected wind turbine in [8]. A unified STATCOM and battery energy storage system is evaluated for the enhancement of dynamic, transient stability, and transmission competence in [9]. In [10], STATCOM is used for transient stability enhancement. Modelling of non-linear load with STATCOM is conducted in [11]. An ultra-capacitor is used with the STATCOM for power oscillation damping in [12]. In [13], a superconducting magnetic energy storage system with STATCOM is used for power system oscillation damping. In [14], steady state performance has been checked with STATCOM and an energy storage system. Sub-synchronous oscillations are mitigated with a superconducting magnetic energy storage system in [15]. In [16], rotor angle and voltage stability were studied during fault conditions with fault location identification. In [17], voltage stability assessment in real time was conducted. A brief summary of different FACTS controller types with a focus on STATCOM topologies and their control strategies was done in [18]. In all the above studies, focus was towards steady state, transient state, dynamic state stability, rotor angle stability, or mitigation of sub-synchronous oscillations of the network, which are conducted by using STATCOM or an energy storage system. Little focus has been given in the enhancement of STATCOM performance by connecting SC during various conditions. Very few researches tested SC with shunt FACTS devices under transient disturbances in multi-machine networks.

In this paper, a storage device (SC) is connected to the STATCOM capacitor for improving its secondary performance under sudden large disturbances in the power network. The short duration application of the SC during disturbance conditions is tested in MATLAB environment. The voltage source converter based STATCOM is designed to provide voltage support by reactive power control and to enhance

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secondary functions, e.g. reduction in power oscillation damping and improvement in transient stability and security of the multi-machine network. The sudden large disturbances are created by three phase faults of 0.3 and 0.2s duration in a multimachine network. Comparative analysis of STATCOM with storage device and without storage devices is conducted. The results prove the improved STATCOM performance with the SC during the transient problem.

II. MODELLING OF THE POWER NETWORK

A multi-machine network during transient conditions is considered. A synchronous generator, two loads, and a transformer are connected with the STATCOM and the supercapacitor is connected in shunt. As case studies, three-phase faults are applied for transient conditions near the transformer.

A. Synchronous Generator

The synchronous generator is an electrical machine converting mechanical into electrical power. It is the chief driver of any power network. The synchronous generator plays a very important role in the monitoring of the power network at various conditions [10]. Model (1.1) of IEEE Task Force, with one equivalent damper winding on the q-axis with field circuit is represented as [11]:

$$\frac{d\delta}{dt} = \omega_B (S_m - S_{mo}) \quad (1)$$

$$\frac{dS_m}{dt} = \frac{1}{2H}[-D (S_m - S_{mo}) + T_m - T_e] \quad (2)$$

$$\frac{dE'_q}{dt} = \frac{1}{T'_{do}}[-E'_q + (x_d - x'_d)i_d + E_{fd}] \quad (3)$$

$$\frac{dE'_d}{dt} = \frac{1}{T'_{qo}}[-E'_d - (x_q - x'_q)i_q] \quad (4)$$

The electrical torque equation is given as:

$$T_e = E'_d i_d + E'_q i_q + (x'_d - x'_q) i_d i_q \quad (5)$$

where δ is the operating rotor angle, ω_B is the rated angular speed, S_m and S_{mo} represent the slip, H is the generator inertia constant, D is the damping coefficient, T_m and T_e represent the mechanical and electrical torque, E'_d and E'_q are the voltages for d and q axes, T'_{do} and T'_{qo} are the open circuit transient time constants for direct and quadrature axes, x_d, x'_d, x_q, x'_q, i_d, and i_q are the reactances and currents of the said two axes, and E_{fd} is the output of the dynamic system.

B. Static Synchronous Compensator (STATCOM)

The STATCOM and the Static VAR compensator are members of the FACTS family which are shunt-connected devices. The STATCOM helps to control the power and enhances transient stability of power grids [1]. STATCOM can generate more reactive power than Static VAR compensator during voltage lower than the normal voltage regulation range. The STATCOM has the ability to provide more capacitive reactive power during fault conditions. STATCOM regulates both inductive and capacitive modes according to the action of injection or absorption of the reactive power [12, 13]. Reactive power variation is performed by the voltage source converter coupled to the coupling transformer [14, 20]. The equivalent circuit of a STATCOM with a SC is shown in Figure 1.

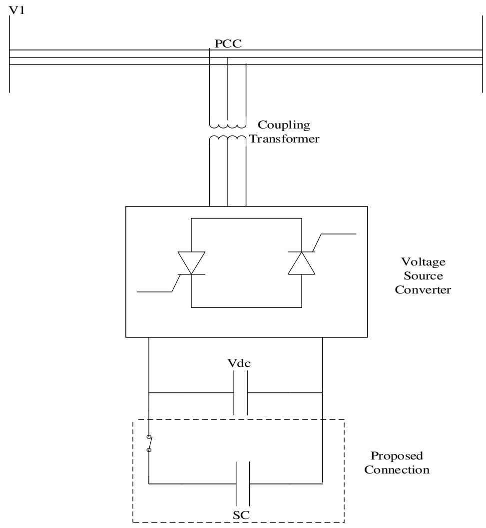

Fig. 1. Equivalent circuit of STATCOM with an SC.

Mathematically, the active and reactive powers of the STATCOM are represented as:

$$P = \frac{V_1 V_2}{X} \sin\delta \quad (6)$$

$$Q = \frac{V_1(V_1 - V_2\cos\delta)}{X} \quad (7)$$

Figure 2 shows the control network block diagram of a STATCOM with an SC. It comprises of a phase locked loop which calculates the phase voltage and the three phase AC current for the direct-axis and quadrature-axis components, the measurement system for measuring the d and q components of the AC positive-sequence voltage, the currents to be controlled, the DC voltage V_{dc}, and the AC and DC voltage regulators for controlling reactive and active power flow respectively. The current regulator controls the magnitude and the phase by the Pulse Width Modulator converter. The SC is connected across V_{dc}.

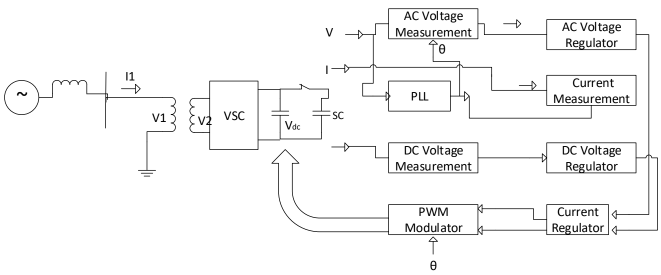

Fig. 2. Block diagram of the control network of a STATCOM with an SC.

C. Super-Capacitor

An SC, also known as an ultra-capacitor, is an electrochemical double layer capacitor. The values of capacitance of the super-capacitor are orders of magnitude greater than the values of normal capacitors. SCs can deliver bursts of energy since charging and discharging takes place rapidly. Using a single SC block, modeling can be done by connecting the SC's cell in series or parallel. Beside the energy storing capacity as an advantage, when the SC is combined with STATCOM, the performance of the network is enhanced with active power support to the network. The equivalent circuit for a single cell in the SC block is shown in Figure 3.

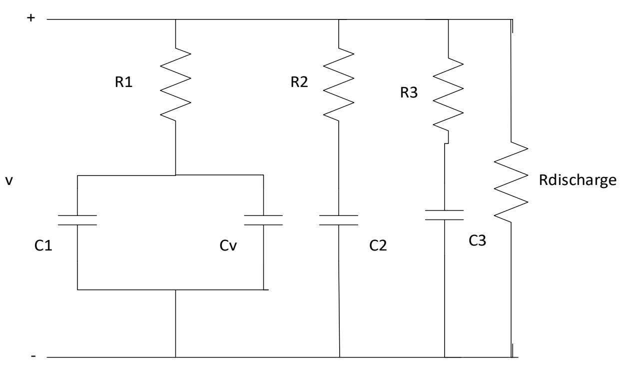

Fig. 3. A single cell SC.

The voltage and current across the SC block are obtained by:

$$V_{cn} = \frac{v}{N_{series}} - i_n R_n \quad (8)$$

$$i_n = C_n \frac{dV_{cn}}{dt} \quad (9)$$

where V is the voltage across the block, N_{series} is the number of series cells, n is the branch number, i_n is the n^{th} branch current, R_n is the n^{th} branch resistance, and V_{cn} is the n^{th} branch voltage across the capacitor.

III. Test Network

In order to check the performance of the power network during transient condition, a 4-bus test network is considered (Figure 4). The test network consists of 3 generators, 2 loads, 1 transformer, 3 lines, and 4 buses. The basic test network is modeled in MATLAB/Simulink environment with the following parameters: The generators have 16,500MVA total generation capacity, the loads have 12,500MW loading, one 1000MVA transformer is used, a VSC based 100MVA STATCOM, 500KV Voltage, and a 100pF, 16V SC.

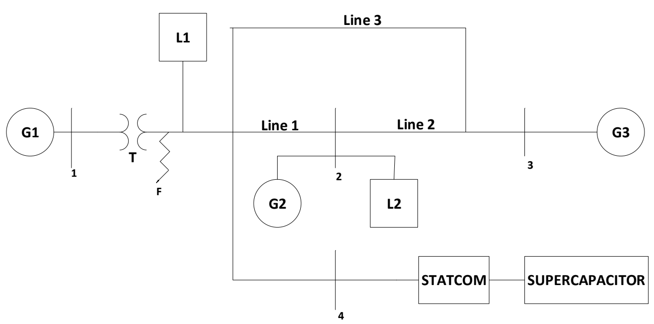

Fig. 4. Test network single line diagram.

IV. Simulation Performance

Simulation performance is checked by applying 3-phase faults of 0.2 and 0.3s duration near bus 1, which implies a transient condition. Various parameters like rotor speed, stator voltage, true power, imaginary power, and voltages are monitored. Transient conditions or large disturbances result into very unbalanced network parameters and create tremendous oscillations in the network, upshots, or complete black-outs or total failures. It is better to prevent such types of failure by connecting some boosting or balancing elements. Flexible AC transmission system elements are power devices connected to the network for enhancement. A STATCOM shunt FACTS device is connected in the network at bus 4 to support the network during disturbance conditions.

Figure 5 displays the rotor speed of the generator connected to bus 1. A 3-phase fault is applied for 0.2 and 0.3s. The network without STATCOM and SC shows more oscillations and takes more time to return to the stable condition. As compared to the earlier condition, the connected STATCOM stabilizes rotor speed early, with fewer oscillations. The result of connecting the SC with the STATCOM is more impressive because it damps rotor speed oscillations in less settling time. Figure 5 indicates effective large fault duration condition and oscillation suppression by the SC-based STATCOM and thus, reduced settling time of the rotor speed.

Figure 6 depicts the Generator 1 terminal voltage without STATCOM and SC, with STATCOM and SC, and with STATCOM only. As the fault duration increases, the system becomes more prone to instability. With STATCOM and SC stator, the Voltage comes closer to 1pu earlier and thus the stability margin increases. During the transient period, the SC suppresses the oscillations and superior performance of the STATCOM is observed.

(a)

(b)

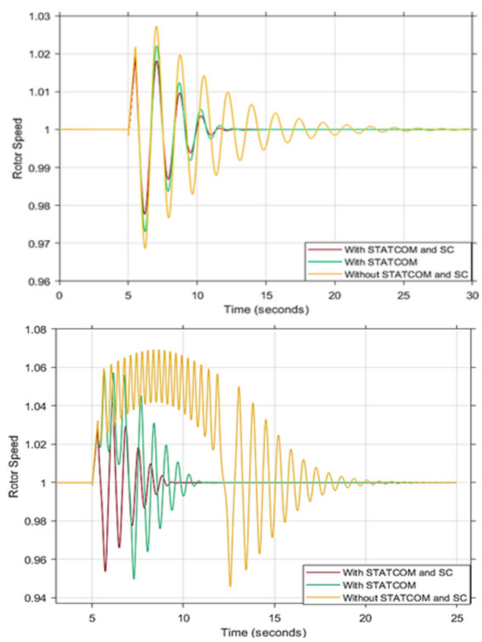

Fig. 5. Rotor speed, fault time (a) 0.2s, (b) 0.3s.

(a)

(b)

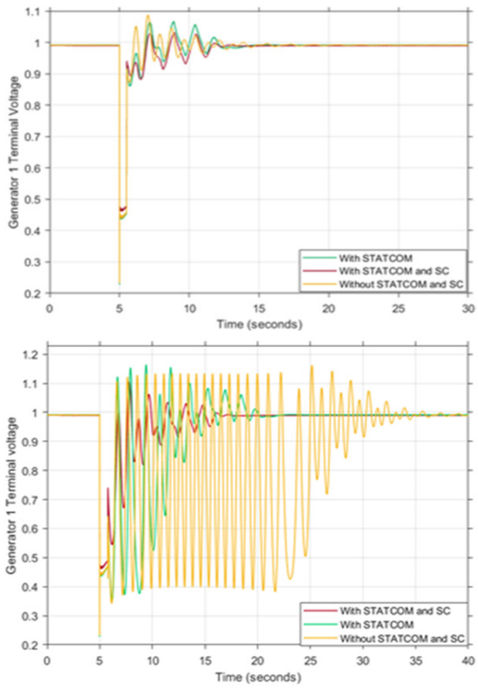

Fig. 6. Generator 1 terminal Voltage, fault time (a) 0.2s, (b) 0.3s.

(a)

(b)

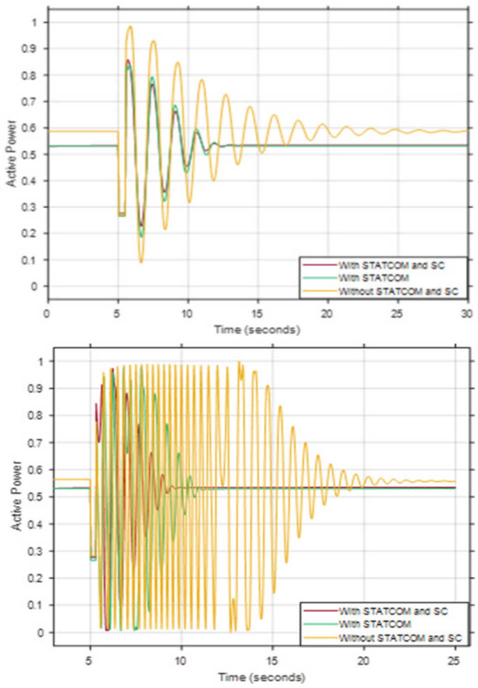

Fig. 7. Active Power, fault time (a) 0.2s, (b) 0.3s.

(a)

(b)

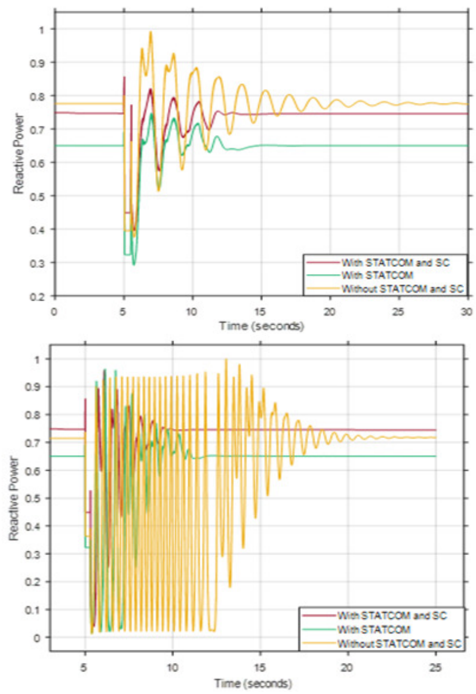

Fig. 8. Reactive power, fault time: (a) 0.2s, (b) 0.3s.

(a)

(b)

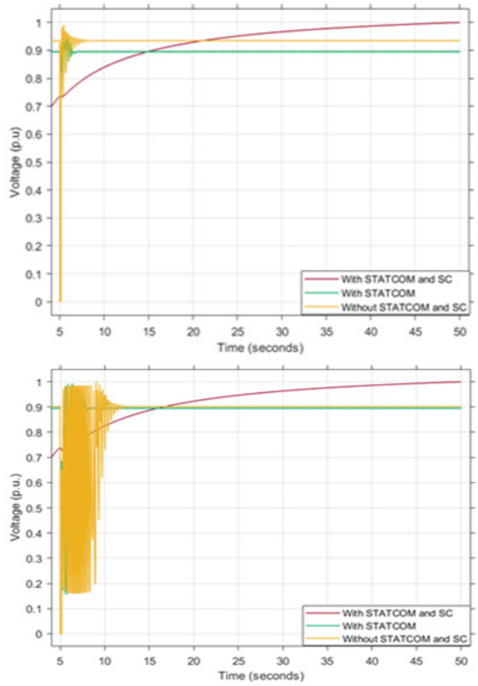

Fig. 9. Network Voltage at bus 2, fault time (a) 0.2s, (b) 0.3s.

Active power and reactive power oscillation damping is more effectively done with STATCOM and SC as can be seen in Figures 7 and 8. Larger oscillations are observed in the 0.3s fault duration. STATCOM with SC real power oscillations are effectively damp out and settling time reduces with a large stability margin. Reactive power demand reduces and oscillations reduce as well.

Figure 9 exhibits the bus 2 Voltage oscillations, which are maintained at 1pu with the SC-based STATCOM combination. Figure 10 shows the V_{dc} variation with an SC. The DC voltage is maintained constant. Figure 11 shows the SC voltage variation during fault conditions.

(a)

(b)

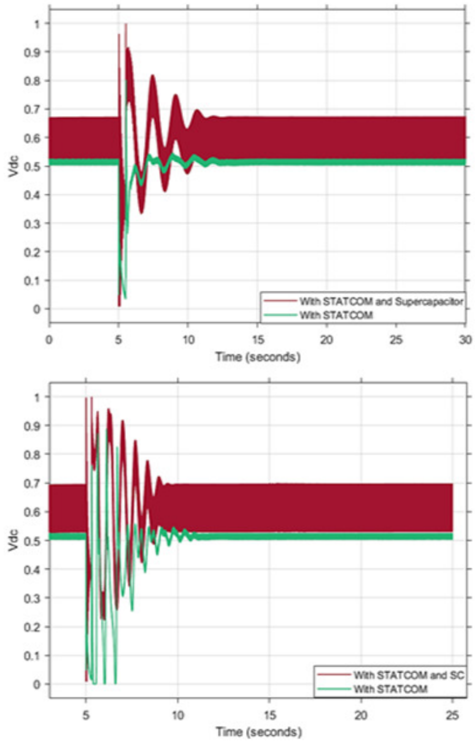

Fig. 10. V_{dc}, fault time (a) 0.2s, (b) 0.3s.

(a)

(b)

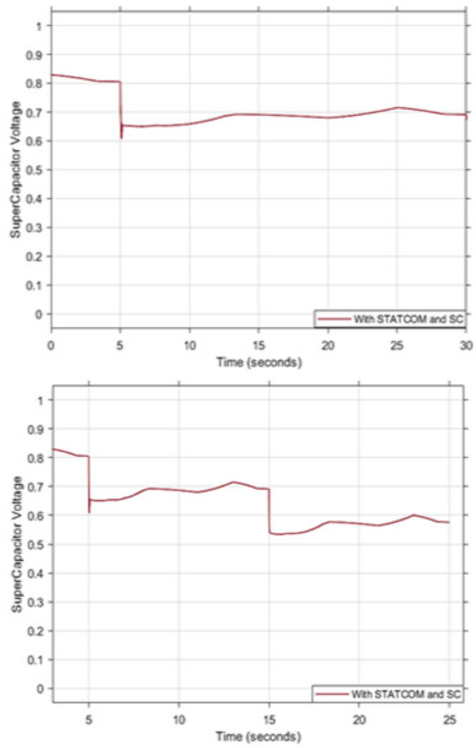

Fig. 11. SC Voltage, fault time (a) 0.2s, (b) 0.3s.

V. CONLCUSION

In this paper, the performance of the Static Synchronous Compensator (STATCOM) is enhanced with the aid of a Super-Capacitor (SC). A multi-machine network was evaluated in MATLAB during the transient condition without STATCOM, with STATCOM and with both STATCOM and SC. A symmetrical 3-phase fault is applied for 0.2s as case study 1 in the network. It is observed that the oscillations are damped within 25, 12, and 105s without STATCOM, with STATCOM, and with STATCOM-SC respectively. With STATCOM-SC, the second peak reduces from 1.025 to 1.015pu. The primary function of a STATCOM is to maintain constant terminal voltage and bus voltage at 0.9 to 1pu, which is achieved by the proposed STATCOM-SC combination. Similarly for the case study 2, the fault duration is 0.3s, for which the responses of STATCOM-SC are drastically enhanced as network oscillations are damped quickly, peak time and Voltage variation are reduced, and the network quickly overcomes the issue.

It is observed that as the fault duration increases, the proposed STATCOM-SC model works more effectively. An additional benefit to true power compensation is the energy storage which is very essential for secured power network. The energy storage with STATCOM-SC enhances the transient performance of the network and reduces the damage to the equipment during sudden large disturbances, which have not been tested in the published research work. SCs are preferred for short duration applications of nearly 30 to 40s. In the simulations of the current study, the system was tested for 25 to 30s after the disturbance.

REFERENCES

[1] N. G. Hingorani and L. Gyugyi, *Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems*, 1st ed. New York, NY, USA: Wiley-IEEE Press, 1999.

[2] C. W. Taylor, *Power System Voltage Stability*. New York, NY, USA: McGraw-Hill, 1993.

[3] P. Srithorn, M. Sumner, L. Yao, and R. Parashar, "A STATCOM with supercapacitors for enhanced power system stability," in *2008 4th IET Conference on Power Electronics, Machines and Drives*, York, UK, Apr. 2008, pp. 96–100, https://doi.org/10.1049/cp:20080490.

[4] H. Xie, L. Angquist, and H.-P. Nee, "Design Study of a Converter Interface Interconnecting Energy Storage With the DC Link of a StatCom," *IEEE Transactions on Power Delivery*, vol. 26, no. 4, pp. 2676–2686, Jul. 2011, https://doi.org/10.1109/TPWRD.2011.2161677.

[5] P. Wang, Y. Wang, N. Jiang, and W. Gu, "A comprehensive improved coordinated control strategy for a STATCOM integrated HVDC system with enhanced steady/transient state behaviors," *International Journal of Electrical Power & Energy Systems*, vol. 121, Oct. 2020, Art. no. 106091, https://doi.org/10.1016/j.ijepes.2020.106091.

[6] O. B. Adewuyi, R. Shigenobu, K. Ooya, T. Senjyu, and A. M. Howlader, "Static voltage stability improvement with battery energy storage considering optimal control of active and reactive power injection," *Electric Power Systems Research*, vol. 172, pp. 303–312, Jul. 2019, https://doi.org/10.1016/j.epsr.2019.04.004.

[7] D. Chatterjee and A. Ghosh, "Improvement of transient stability of power systems with STATCOM-controller using trajectory sensitivity," *International Journal of Electrical Power & Energy Systems*, vol. 33, no. 3, pp. 531–539, Mar. 2011, https://doi.org/10.1016/j.ijepes.2010.12.005.

[8] M. Kenan Döşoğlu and A. B. Arsoy, "Transient modeling and analysis of a DFIG based wind farm with supercapacitor energy storage,"

International Journal of Electrical Power & Energy Systems, vol. 78, pp. 414–421, Jun. 2016, https://doi.org/10.1016/j.ijepes.2015.12.020.

[9] Z. Yang, C. Shen, L. Zhang, M. L. Crow, and S. Atcitty, "Integration of a StatCom and battery energy storage," *IEEE Transactions on Power Systems*, vol. 16, no. 2, pp. 254–260, Feb. 2001, https://doi.org/10.1109/59.918295.

[10] M. M. N. Akhtar and V. K. Chandrakar, "Security Enhancement of Hybrid Source in the Grid with STATCOM," in *2019 3rd International conference on Electronics, Communication and Aerospace Technology (ICECA)*, Coimbatore, India, Jun. 2019, pp. 49–54, https://doi.org/10.1109/ICECA.2019.8821798.

[11] M. V. Wankhede and V. K. Chandrakar, "Static Synchronous Compensator (STATCOM) for the improvement of the Electrical System performance with Non Linear load," *International Journal of Power Systems*, vol. 1, pp. 27–32, 2016.

[12] K. Dayalal Joshi and V. Chandrakar, "Power oscillation damping using ultracapcitor and voltage source based FACTS controllers," in *2017 IEEE International Conference on Electrical, Instrumentation and Communication Engineering (ICEICE)*, Karur, India, Apr. 2017, pp. 1–6, https://doi.org/10.1109/ICEICE.2017.8191878.

[13] A. M. Raut, K. D. Joshi, and V. K. Chandrakar, "Damping of Power System Oscillation using STATCOM Integrated with SMES," *International Journal of Computer Applications*, vol. 119, no. 8, pp. 11–14, Jun. 2015.

[14] P. Mahale, K. D. Joshi, and V. K. Chandrakar, "Static Synchronous Compensator (STATCOM) with Energy Storage," in *2009 Second International Conference on Emerging Trends in Engineering & Technology*, Nagpur, India, Sep. 2009, pp. 560–563, https://doi.org/10.1109/ICETET.2009.213.

[15] W. Gil-González, O. D. Montoya, and A. Garces, "Control of a SMES for mitigating subsynchronous oscillations in power systems: A PBC-PI approach," *Journal of Energy Storage*, vol. 20, pp. 163–172, Dec. 2018, https://doi.org/10.1016/j.est.2018.09.001.

[16] H. F. Khan, A. H. Hanif, and N. Anwar, "Rotor Angle and Voltage Stability Analysis with Fault Location Identification on the IEEE 9 Bus System," *Engineering, Technology & Applied Science Research*, vol. 10, no. 1, pp. 5259–5264, Feb. 2020, https://doi.org/10.48084/etasr.3175.

[17] D. V. Ngo, K. V. Pham, D. D. Le, K. H. Le, and K. V. Huynh, "Assessing Power System Stability Following Load Changes and Considering Uncertainty," *Engineering, Technology & Applied Science Research*, vol. 8, no. 2, pp. 2758–2763, Apr. 2018, https://doi.org/10.48084/etasr.1892.

[18] R. Jadeja, S. Patel, and S. Chauhan, "STATCOM – A Preface to Power Quality in Power Systems Performance," *Engineering, Technology & Applied Science Research*, vol. 6, no. 1, pp. 895–905, Feb. 2016, https://doi.org/10.48084/etasr.603.

[19] A. Chakraborty, S. K. Musunuri, A. K. Srivastava, and A. K. Kondabathini, "Integrating STATCOM and Battery Energy Storage System for Power System Transient Stability: A Review and Application," *Advances in Power Electronics*, vol. 2012, Dec. 2012, Art. no. e676010, https://doi.org/10.1155/2012/676010.