# Modular Multilevel Converter based Hybrid Energy Storage System

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***Abstract*—A new configuration for integration of hybrid Energy Storage System (ESS) into a STATCOM is presented in this paper. The configuration offers STATCOM features and has ability to support active power at different time scale. The configuration can be called as E-STATCOM, where 'E' stands for Energy Storage. Here, the E-STATCOM is configured around a Modular Multilevel Converter (MMC). The battery is connected at the DC link of MMC through series connected DC-DC converters. On the other hand, supercapacitors are connected in each submodule of MMC. The combination of battery and supercapacitor yields better transient performance, improved battery life-span and compact sizing of ESS. In this work, E-STATCOM is used to address some issues related to grid integration of Wind Energy Generating System (WEGS). Under MPPT operation, the WEGS generates fluctuating power which may affect voltage and frequency stability of the grid. Here, the E-STATCOM absorbs the fluctuation and provides smooth power to the grid, which ensures voltage and frequency stability. The proposed configuration is suitable for high power level, as well as, high voltage level compared to conventional two-level converter based solution. The complete system along with control algorithms are simulated in PSCAD and the results are presented. The simulation results show the effectiveness of the proposed concept.**

***Index Terms*—MMC, STATCOM, Battery Energy Storage System, Supercapacitor, Wind Energy Generation System.**

## I. Introduction

Grid connected WEGS are widely installed all over the world due to environmental concern, reduction in their installation cost, low operational cost and encouragement through government policies. The wind power generating stations are generally operated with Maximum Power Point Tracking (MPPT) control and injects maximum available power into the grid at any instant [1]. So, the wind-power is highly variable considering intermittent behavior of nature. This causes voltage and frequency instability when the wind power is significant compared to grid power. Besides this, the interfacing converters can deliver only a limited amount of reactive power due to their rating constraint. Also, they may inject harmonics into the grid due to their low frequency operation to achieve higher efficiency [2]. These causes various power quality issues as listed below [3].

- Voltage variation and flicker in PCC voltages,
- Variable power injection into the grid,
- Instability during fault condition,
- Harmonic resonance, and
- Low Voltage Ride Through.

Among the various issues, this paper focuses on the mitigation of voltage fluctuations at PCC and smoothening of active power generated by WEGS. A STATCOM can be used to mitigate the power quality issues, whereas ESS can be employed to absorb power fluctuation. Therefore, with the help of STATCOM and ESS, it is possible to inject constant wind power into the grid complying grid codes [3], though there is fluctuation in the wind power.

Instead of using two different systems, e.g. STATCOM and ESS, one single system can be used which has the features of 'STATCOM' and has the ability to provide active power support for definite time scale. This kind of system is termed as 'E-STATCOM' (STATCOM + ESS). A two-level converter based E-STATCOM is reported in [4], where battery is integrated at the DC link. The main limitations of a two-level converter based E-STATCOM are: (i) comparatively lower efficiency ( 96%-97%), (ii) high THD, (iii) large footprint due to need of passive filters, (iv) less redundancy, as the energy storage is lumped at DC link, etc.. Also, two-level converter is not suitable for high voltage and high power applications. The modular multilevel converters are quite good for high voltage and high power applications due to modular structure, redundancy, higher efficiency. An MMC based BESS is reported in [5].

Different kinds of ESS for renewable energy integration are available, which are briefly presented in [6]. Among them, batteries and supercapacitor are popular. Battery is suitable for high power density applications [1], whereas supercapacitors [7] are good for high energy density applications. So, the use of only one kind of energy storage, e.g. either battery or supercapacitor may not be optimal for some applications which demand both high power density and high energy density.

In this paper, both battery and supercapacitor are used for active power support. With the help of hybrid ESS, battery lifespan is improved, dynamic performance becomes better, and size of the ESS is reduced. Due to difference in their characteristics and available voltage ratings [8], [9], interfacing

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DC-DC converters are required for the integration of ESS into MMC. The E-STATCOM with hybrid ESS is employed to integrate large wind farm into the grid complying grid codes. The E-STATCOM absorbs power fluctuations (which is generated by wind farm) and injects smooth power into the grid. It also takes care the power quality issues. The charging/discharging as per the characteristics of battery and supercapacitor are performed through the control of DC-DC converter. The complete control of E-STATCOM is verified through PSCAD simulation and the results are presented here with supporting analysis.

This paper is divided into six sections. Section-I introduces the concept of E-STATCOM. Section-II briefly describes the system under consideration. The proposed configuration and issues related to ESS integration are presented in Section-III. Control methodology of MMC and hybrid-ESS are elaborated in section-IV. The simulation results are presented in section-V. Finally, Section-VI concludes the work.

## II. System under consideration

Fig.1(a) shows a grid connected wind energy generation system. Here each Wind Turbine (WT) is connected to a DFIG for generating power ($P_{wp}$). A local collection bus is formed to accumulate the power generated by wind turbines. The local collection bus is connected to the grid through a step-up transformer. The DFIG is controlled by two back-to-back converters which are placed at the rotor side. They will help DFIGs to generate power at sub-synchronous, as well as super-synchronous speed. The DFIGs are operated in MPPT control [1] to extract maximum available wind power at any instant. Rating of each WT is 1.5MW and corresponding parameters of DFIG are given in Appendix-A [10]. The total power supplied by the wind farm is 10MW. As the WTs are operated under MPPT control, the wind farm generates power which is fluctuating in nature due to the variation of wind speed. The E-STATCOM is connected at the PCC. It absorbs power fluctuation and provides reactive power support to ensure voltage and frequency stabilization of the grid.

## III. Proposed Topology of E-STATCOM

The proposed configuration of MMC based E-STATCOM with hybrid-ESS is shown in fig.2(a). Each leg of MMC consists of two arms, namely positive-arm and negative-arm. Half bridge submodule (SM) is used to form the arm. So, the output voltage of a submodule ($V_{SM}$) is either 0 or $V_c$, (where $V_c$ is the capacitor voltage of a submodule), when it is bypassed or inserted, respectively. Complete DC link voltage of MMC is distributed among the sub-module capacitors of an arm. Hence, the nominal voltage of each SM capacitor ($V_c^{nom}$) is given by (1). During steady-state operation, all the SM capacitor voltages are to be balanced at their respective $V_c^{nom}$. In order to balance the submodule capacitor voltages, sorting algorithm is used in this work [11]. With this method, charging and dis-charging periods of each SM are controlled to regulate the capacitor voltages. A phase-shifted PWM technique is used to generated number of submodules ($N_{sm}$) to be inserted

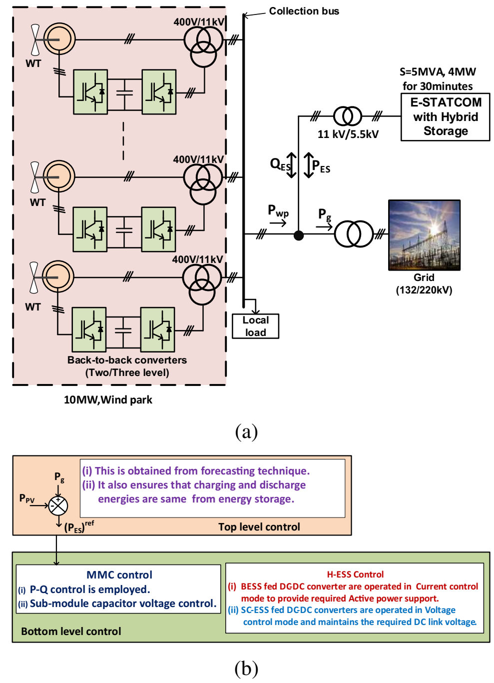



Fig. 1: (a) Grid connected WEGS with H-ESS based E-STATCOM, (b) Overview of E-STATCOM control

at any instant. The sorting algorithm generates gate pulses depending on $N_{sm}$ and direction of arm current.

$$V_c^{nom} = \frac{V_{dc}}{N} \tag{1}$$

To obtain active power support from E-STATCOM, hybrid ESS are integrated into MMC. BESS is distributed at the submodules of MMC and supercapacitors are connected at the DC-link. The available voltage of energy storage units ranges from $12V$ to $125V$. To integrated these modules with MMC, bi-directional DC-DC converters are used. Fig.3 shows structure of the DC-DC converter which is used to integrate battery and supercapacitor. This helps to maintain desired charging/discharging profile of the ESS keeping the other functionalities of MMC intact. At the DC link of MMC, the DC-DC converters are cascaded in series to obtain the required DC link voltage for MMC operation (as shown in fig.2(b)).

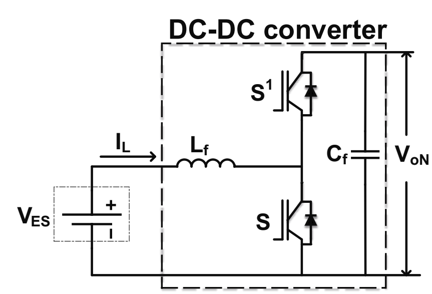
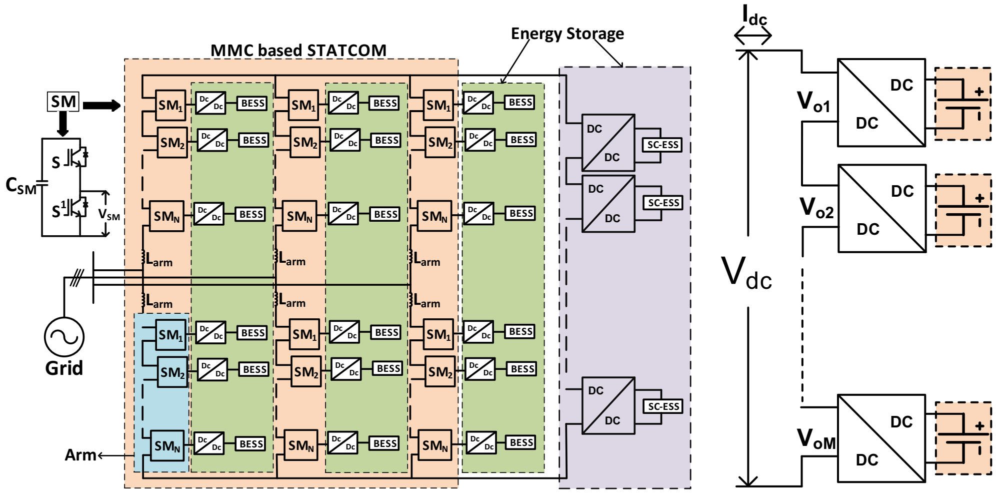



Fig. 3: Bi-directional DC-DC converter for ES integration

Following are the advantages of proposed configuration for E-STATCOM using hybrid-ESS




(a) (b)

Fig. 2: (a) MMC based Hybrid Energy Storage system, (b) Cascaded DC-DC converter connected at DC link

- The efficiency is high compared to the conventional two/three level converter based topologies.
- Redundancy is high as the energy storage systems are distributed.
- Modularity is also high.
- It supports both high power density and high energy density applications due to the presence of battery and supercapacitors.

Due to the use of hybrid energy storage system, the following advantages are obtained.

- Battery lifespan is improved.
- Transient performance becomes better.
- Size of the ESS is reduced.

## IV. Control of E-STATCOM

The main objectives of E-STATCOM are to absorb power fluctuation and to provide required reactive power support at PCC. To fulfill these objectives, control methodology for the system is shown in fig.1(b). The complete control of E-STATCOM is divided into two parts, which are (i) control of MMC, and (ii) control of DC-DC converters. Here, the MMC is operated in $P-Q$ control mode. The DC-DC converters in the DC-link are operated in voltage control mode, whereas the DC-DC converters in submodules are operated in current control mode. The active power reference to the MMC is calculated through the following equation.

$$P_{ES}^{ref} = P_G - P_{wp} \tag{2}$$

where $P_G$, $P_{wp}$ and $P_{ES}^{ref}$ are power injected into the grid, power generated by WEGS and active power support from E-STATCOM respectively.

### A. Control of MMC

For effective operation of MMC, its control is further divided into outer-loop and inner-loop controls. Fig. 4(a) shows the block diagram of outer-loop control. The modulating signal for required $P$ and $Q$ are generated through this control. Here, the P-Q controller is implemented in synchronous $d-q$ reference frame, where $d$-axis is aligned along the grid voltage vector. So, the required active power support from E-STATCOM i.e., $P_{ES}^{ref}$ can be obtained by varying $i_d^*$. Similarly, the reactive power support can be obtained by adjusting $i_q^*$. Hence, the references for $i_d$ and $i_q$ are generated according to (3) and (4) respectively. In the inner loop control, sorting algorithm [11] is used for submodule capacitor voltage balance. The flowchart for the implementation of sorting algorithm is shown in Fig.4(b).

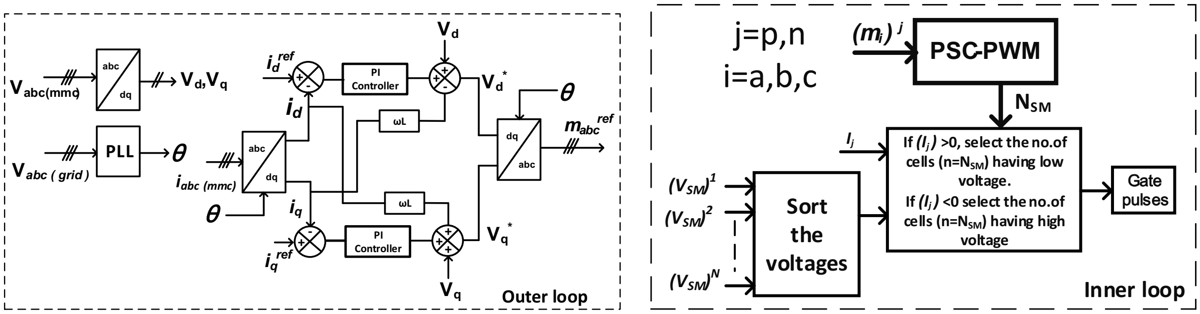
$$i_{dref} = \frac{2}{3}\frac{P_{ES}^{ref}}{V_d} \tag{3}$$

$$i_{qref} = -\frac{2}{3}\frac{Q_{ref}}{V_d} \tag{4}$$

The H-ESS for the proposed E-STATCOM is formed by using BESS and SC-ESS. To regulate the active power support from battery and supercapacitor, complete control of H-ESS is split into 'SC-ESS control' and 'BESS control' respectively (as shown in Fig.1(b)).

### B. Control of BESS

The BESS are connected to the submodules through DC-DC converters. The DC-DC converters are operated in current control mode (CCM) to provide active power. Due to the presence of DC-DC converter, the charging and discharging of the BESS can be controlled as per the datasheet characteristics. The control block diagram is shown in Fig.5, where the term $\alpha$ is used to initiate the control function and to eliminate over/under charging of the modules. The inductor current reference ($I_L^*$) can be calculated as follows.




(a) (b)

Fig. 4: (a) Outerloop control of MMC for active and reactive power support, (b) Sub-module capacitor voltage balance algorithm

Step-I: In this step, the total active power is segregated between battery and supercapacitor according to (5).

$$P_{es}^{ref} = P_{BESS} + P_{sc} \tag{5}$$

where $P_{BESS}$ is the power which comes from battery and $P_{sc}$ is the power which is supplied by supercapacitors. Here a peak saving method is used to limit the maximum power of the battery.

Step-II: Now this power ($P_{BESS}$) comes from batteries which are connected at each submodule of the MMC. So, the power provided by each battery bank (connected at the submodule) is given by

$$P_{SM} = \frac{P_{BESS}}{6N} \tag{6}$$

where $N$ is the number of submodule per arm. The inductor current reference can be expressed as:

$$I_L = \frac{P_{BESS}}{6N \times V_{bess}} \tag{7}$$

where $V_{bess}$ is the voltage across the battery bank of each submodule.

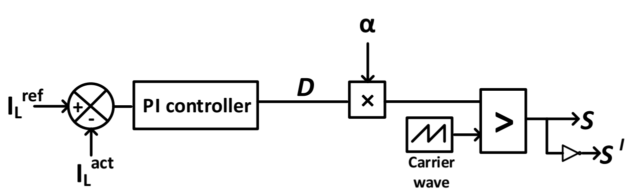



Fig. 5: Control block diagram of BESS fed DC-DC converter

## C. Control of SC-ESS

The supercapacitors are connected at the DC-link of MMC through DC-DC converters. The DC-DC converters are connected in series and form the DC-link. Each DC-DC converter is operated in Voltage Control Mode (VCM) to maintain a fixed DC-link voltage. So, the DC-link voltage can be written as:

$$V_{dc} = \sum_{m=1}^{M} V_{om} \tag{8}$$

where $V_{om}$ is the output of a DC-DC converter. Considering equal voltage sharing among the DC-DC converters, it can be written as follows.

$$V_{om} = \frac{V_{dc}}{M} \tag{9}$$

where $M$ is the number of DC-DC converters connected in between the DC-link. With the help of controller, as shown in Fig.6, output voltage of each DC-DC converter is regulated at $\frac{V_{DC}}{M}$.

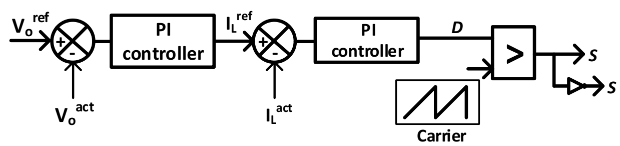


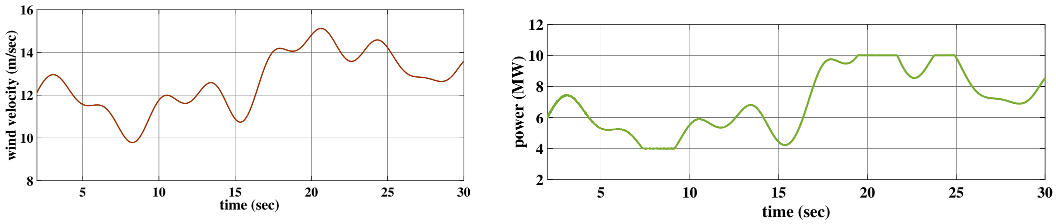

Fig. 6: Control block diagram of supercapacitor fed DC-DC converter

## V. Simulation Results and Discussion

Rating of MMC based E-STATCOM employed in this work is given in Appendix-B. An equivalent model of Wind farm as shown in Fig.1(a) is developed in PSCAD. Data for the wind speed is obtained from Charanka project, located in Gujarat state in India. The wind speed is recorded during 01:30pm to 02:00pm of 17th November 2015 [12]. Fig.7(a) shows the variation of wind speed for a period of 30 minutes. The curve-fitting method is used to develop mathematical expressions to model the wind profile. The power generated by WEGS corresponding to the wind profile is shown in Fig.7(b).

### A. Power smoothening by E-STATCOM

An E-STATCOM is employed at PCC of wind farm, as shown in Fig. 1(a). The purpose of the E-STATCOM is to absorb the power fluctuation which is mainly caused due to the variation of wind speed. The active power generated by the E-STATCOM (where $P_{es} = P_{wp} - P_g$) is shown in Fig.8. This ensures constant power injection into the grid which is set at $7.15MW$ even though wind power ($P_{wp}$) is fluctuating. After compensation, the grid power is presented in Fig.8, which is constant over the period. The E-STATCOM also injects some amount of reactive power into the grid for voltage support as shown in Fig. 8.




(a) (b)

Fig. 7: (a) Profile of wind velocity, (b) Power generated by the wind park

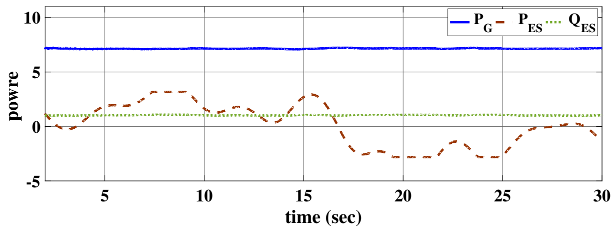



Fig. 8: Active and reactive power support from E-STATCOM

### *B. Performance of MMC control*

The proposed configuration is operated under $P-Q$ control mode. The DC-link voltage is kept constant through the operation. The energy from the ES (i.e. supercapacitors and battries) is first shifted to the submodule capacitors, and from there it is taken out to the grid through $P-Q$ control. The voltage balance among the submodule capacitors is arried out through sorting algorithm. The submodule capacitor voltages are shown in Fig.10(a) and Fig.10(b) for upper arm and lower arm of phase-a respectively. It is observed that the submodule capacitor voltages of MMC are maintained at their nominal value of 3kV (as given in Appendix-B). Note that the magnitude of the ripple voltage in the submodule capacitor is less than $10\%$, which is at per with the industrial standards. The converter currents and the corresponding upper and lower arm currents for phase-a of MMC are presented in Fig.9 and Fig.10 respectively. The 2nd harmonic component in the arm current is reduced by a resonant type circulating current controller.

### *C. Power support from BESS and supercapacitors*

The BESS are connected at the submodules of MMC through DC-DC converters which are operated in current control mode (as discussed in sub-section IV-B). The reference and actual current through the inductor are shown in Fig.11. Fig.12 shows the power which is given by BESS. It is noticed that maximum power from BESS is limited to $2MW$. The remaining power above 2 MW is obtained from supercapacitors which are distributed at the DC link.

The DC-DC converters in the DC-link is operated in voltage control mode (as discussed in sub-section:IV-C) to maintain the DC-link voltage constant at 12 kV during operation. The DC-link voltage is shown in Fig.13, where output of each DC-DC converter is regulated at 3 kV. The rating of BESS and SC-ESS for active power support are given in Appendix-C and D.

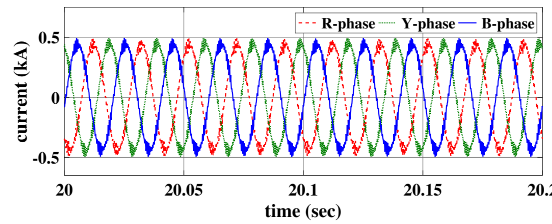
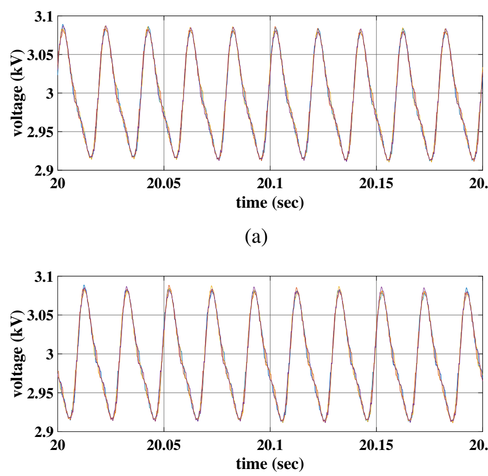



Fig. 9: Three phase currents of E-STATCOM




(a)

(b)

Fig. 10: Submodule capacitor voltages (a) upper arm, (b) lower arm

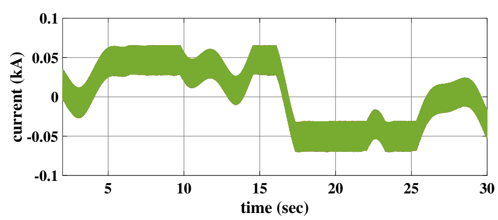



Fig. 11: Actual and reference currents drawn from BESS at the sub-module

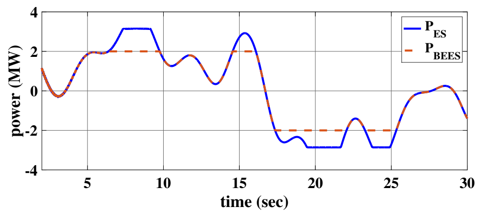



Fig. 12: Active power support from BESS

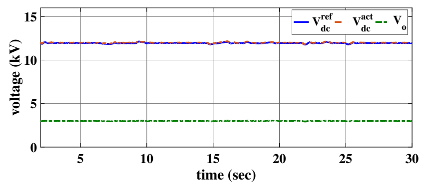



Fig. 13: Reference and actual voltages of DC link along with output voltages of each DC-DC converters at the DC link

## VI. Conclusion

This paper has proposed a new configuration of E-STATCOM for high-voltage and high-power applications. The E-STATCOM is formed by integrating hybrid energy storage systems (i.e. battery + supercapacitor) into an MMC. The beauty of this configuration is that two different types of storage systems are integrated into MMC without increasing the level of circulating current. This is happened by decoupling the control of battery and supercapacitors. Note that the batteries are supplying active power under CCM, whereas the supercapacitors are supplying active power under VCM. Bi-directional DC-DC converters with VCM/CCM are used to integrate the storage elements with MMC. The power upto 2MW comes from battery and remaining power is supplied by the supercapacitor. The efficiency of the configuration is high compared to other conventional approaches, based on two/three level converters. The proposed E-STATCOM is employed for power smoothening of a grid connected WEGS and to support reactive power. These help to improve voltage/frequency stability of the grid. The control of the proposed configuration is checked through PSCAD simulation which performs satisfactorily under the variation of wind speed.

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## Appendix

### A. Parameters of Wind plant

Power rating : 10 MVA
AC Line voltage ($V_L$): 11kV

### B. Parameters of MMC based E-STATCOM

Rating of Converter (S): 10 MVA
Active power Support (P): 3.5 MW
Dc link Voltage ($V_{dc}$): 12 kV
No.of sub-modules per arm (N) : 4
Sub-module voltage ($V_{sm}$) : 3 kV
Sub-module Capacitance ($C_{sm}$) : 5 mF
Arm Inductance ($L_{arm}$) : 2.5 mH

### C. Parameters of Boost DC-DC Converter for BESS integration

Rating of each Converter (P): 0.084 MW
Number of converters ($6N$) : 24
Output voltage of each converter ($V_o$) : 3 kV
Filter Inductance ($L_f$) : 20 mH
Nominal voltage of each BESS module : 1.65 kV
Switching frequency ($f_{sw}$) : 1kHz

### D. Parameters of Boost DC-DC Converter for SC-ESS integration

Rating of each Converter (P): 0.375 MW
Number of converters ($M$) : 4
Output voltage of each converter ($V_o$) : 3 kV
Filter Inductance ($L_f$) : 6 mH
Filter Capacitor ($C_f$) : 2500 uF
Nominal voltage of each SC-ESS module : 1.5 kV
Switching frequency ($f_{sw}$) : 1kHz