[1] Srinu Bhukya

[2]T. Murali Krishna

[3]G. Mallesham,

[4]Ch.Anil Bharadwaj

# Design and Performance Evaluation of Fuzzy Controller based Energy Storage Enabled Statcom for Electrical Distribution Network

***Abstract:*** - In order to fulfill the demand for power, the production of locally accessible resources, such as solar and wind energy, has increased dramatically during the past ten years. Their integration into the distribution of electrical network (EDN) has affected the operation of the network. Variations in the real power flow and an increase in reactive power demand have impacted the EDN voltage/frequency profiles and distribution transformer strain. Hence to improve the voltage regulation and reduce the active power fluctuations, there is a need for a system network of electrical distribution (EDN). It has the ability to support both reactive and active power. Thus, the energy storage device with STATCOM is introduced i.e. an energy storage device linked to Statcom (EsSt) has been proposed in this paper. The Common Coupling Point (CCP) voltage can be adjusted by energy storage connected to Statcom (EsSt) to satisfy the amount of power required actively at EDN. The EsSt has an integrated battery storage system and may be controlled using a voltage source converter by employing the proper control strategy to deliver the necessary energy support and VAR compensation. The voltage at the dc-link has been integrated using DC-DC converter based half bridge. The use of conventional PI controllers provides poor transient response. To improve the transient performance, It is suggested that a fuzzy logic controller be used in place of the PI controller. Analysis of comparison using MATLAB. The rule-based fuzzy logic controller performs better than the PI controller, according to the Simulink environment.

***Keywords:*** Wind power, solar power, two-level converter, battery storage, controller design, DC-DC converter, and active power support.

## I. Introduction

Distributed power generation, which makes use of distant sources like fuel cells, Small-scale wind turbines and solar panels on roofs, has increased in response to the world's expanding need for electricity [1].The market for solar plants and fuel cells has also expanded due to government incentives, improved conversion efficiency technologies, convenience of use, and lower installation costs [2]. However, to increase the customers' confidence in the dependability of their power supply, they have a direct connection to the regional distribution systems. Separation. Due to variations in energy flow, the distribution network's performance and operation have been impacted. Uneven voltage regulation and protection systems have also been an issue, and transformer strain has increased. Distribution dependability has to be improved, which means solar energy-based generating units (GU) must be integrated and consumer loads must be effectively distributed among distribution feeders [3]. Reactive power compensation, energy storage devices (ESD), and GU's active power curtailment were among the strategies used in [4].

In order to minimize fluctuations in active power within the distribution network, an energy storage device must provide the requisite active power adjustment. This saves the extra power produced by the GU and feeds it back to the CCP during periods of high demand. In addition, using storage systems in conjunction with the GU has

[1] *Corresponding author: SRINU BHUKYA [1]Research scholar, Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India-500007.E-Mail:srinu.bhukya@gmail.com

[2]Assoc. Professor, Department of Electrical & Electronics Engineering, Chaitanya Bharati Institute of Technology, Gandipet, Hyderabad, India-500075. Email: tmurali5@gmail.com

[3]Professor, Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India-500007

[4]Staff Engineer, Embedded DVT, Storage Business Unit, Enphase Solar Energy India (Pvt.) Ltd., Bengaluru, Karnataka, 560017.

been suggested in [7]. In this case, the distribution network's node voltage changes have been limited by the use of an ESD. Using static variable compensators or ESD is unnecessary when a single system can offer both reactive power demand and required energy. Within [8], a control system is included for energy storage so that it can give the actual and reactive powers for a GU that is powered by renewable energy. Apart from addressing power quality issues, restoring the power supply to the GU-controlled distribution circuit is a key challenge [9]. The authors in [10] have discussed the suitable control strategy. While the matching process is manageable for medium-sized PV inverters, small-scale PV inverters will find it challenging to employ.

The required active power adjustment must be provided by an energy storage device to lessen the amount of oscillation active power throughout the distribution system. This saves the extra power produced by the GU and feeds it back to the CCP during periods of high demand. In addition, using storage systems in conjunction with the GU has been suggested in [7]. In this case, the distribution network's node voltage changes have been limited by the use of an ESD. It is not necessary to use static variable compensators or ESD when a single system can offer both reactive power demand and required energy. Within [8], a control system is included for energy storage so that it can give the actual and reactive powers for a GU that is powered by renewable energy. Apart from addressing power quality issues, restoring the power supply to the GU-controlled distribution circuit is a key challenge [9]. The authors in [10] have discussed the suitable control strategy. While the matching process is manageable for medium-sized PV inverters, small-scale PV inverters will find it challenging to employ.

As a result, an EsSt that can support grid codes for running networks that are dominated by renewable energy has been proposed in [11]. It has been proved that an EsSt based on a two-level converter can be distributed. Here, the active power is supported by both an ultracapacitor and a battery, increasing the EsSt's installation costs and footprint. As a result, it is clear that in a distribution network where sources of renewable energy predominate, only one energy storage unit is suitable for satisfying the active power requirement. An E-STATCOM (Static Synchronous Compensator) and a battery storage system are combined in this study's novel solution, which is a two-level voltage source converter (VSC) [12]. To enable bi-directional power, the battery used for storage is integrated into the VSC's DC-link via DC-DC half-bridge converter. To decrease the overshoot at the dc-link, this publication suggests replacing the traditional PI controller with an expert controller that uses fuzzy logic [13-17].

The objective is to use a fuzzy controller with a better response to implement a variance in the voltage across the DC-link to improve the transient performance of the voltage (Vdc).Using a fuzzy logic controller instead of a PI controller improves the DC-link voltage's transient performance. The response produced by the fuzzy logic controller is superior to that of the PI controller. The methodology for utilizing modified controller parameters to assess the Energy Storage System (EsSt) performance is outlined in Section 1. The Section-2, Section- 3 provides an expanded description of the EsSt structure. In section 4, the Fuzzy logic controller phenomenon used by the EsSt is covered to operate. In Section 5, we perform a comparison analysis and model EsSt to find the controller parameters. Section 6 describes how EsSt operates with the simulation model created in Matlab simulation.

## II. SYSTEM CONSIDERED FOR THE STUDY

This section outlines the methodology used to assess the EsSt's ability to supply the required active and reactive power and control the CCP voltage. Fig.1 illustrates how this system operates. Fig. 2 shows the location of the PV inverters on the load buses. The PV inverters in this instance are shown in the model as current sources [6]. Additionally considered is an offsite wind based energy conversion system that is directly linked to the CCP of the substation.

### A. Wind energy conversion system:

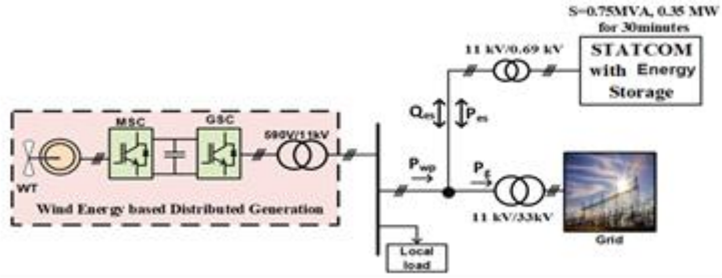



Figure 1: E-STATCOM-equipped wind power generation layout

The illustration shows Fig. 1 an integrated wind-based energy conversion system. The connection between the wind turbine and an asynchronous generator, sometimes called an induction machine or squirrel cage. The machine's operational feasibility is enhanced by connecting it to an ac network via an AC/DC/AC converter. Wind-Powered Energy Conversion System (WECS) has a maximum production capacity of 1 MW. The induction machine's speed is regulated by the machine-side converter (MSC), which also feeds the machine's energy into the DC connection. The Controlling the unstable DC-link voltage enables the Conversion on the grid side (GSC) to function as a rectifier. The WECS rating is described in [18], along with the MSC and GSC control mechanisms.

### B. System for converting solar energy

The diagram shows how the PV panel is connected to the AC terminal at the load points in Fig. 2. Most often, two-stage conversion is used to increase performance. A DC-DC converter with a boost type that is connected to the PV panels powers the PV inverter and enables it to operate at peak efficiency. The maximum power to be supplied into the voltage source converter of the DC-link is provided using a power point tracking technique. When the grid unit (GU) is receiving actual power from the VSC, the DC-DC converter keeps the DC-link capacitor's voltage stable. The solar energy conversion system's (SECS) control concept can be thoroughly explained in [19-22]. Similar concepts have been applied in

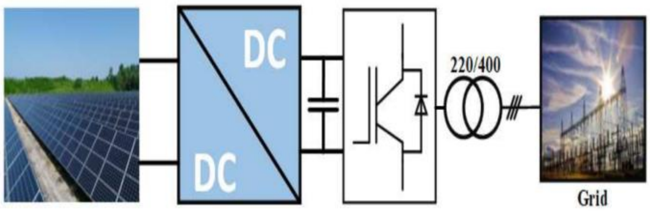



Figure 2: System for converting solar energy into grid electricity in two stages

## III. DESCRIPTION OF STORAGE ENABLED STATCOM

The energy storage enabled STATCOM (EsSt) configuration shown in fig.3. This VSC has two levels and provides both reactive power support and real power support for voltage regulation requirements. By attaching the low voltage storage to the VSC's dc-link, the battery storage system may effectively fulfil its energy needs.

### A. Configuration of STATCOM with storage

The energy storage requirement can be satisfied by using the mechanism for storing batteries. The storage system is linked to the VSC's DC-link.The following section of this manuscript presents the entire VSC control principle. The VSC's overall rating is shown in [12]. The VSC's dc link voltage regulator, the dc-dc converter, is discussed in [20]. The EsSt modeled in [12] was built using a boost-type DC-DC converter.The half bridge DC-DC converter has allowed the battery storage system to be integrated at the VSC's DC-link. A DC-DC converter connects the energy storage system to the EsSt arrangement, which is depicted in Fig. 3.

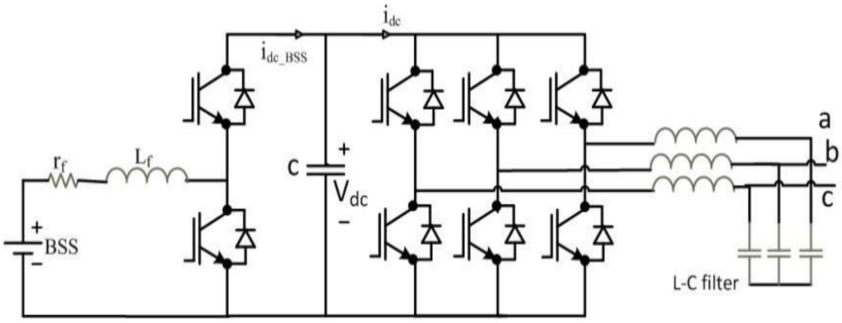



Figure 3:Layout of EsSt

*B. Control of the E-STATCOM*

This region provides an outline of the control principle that will be used to operate the VSC and get the Energy Storage (ES) features. Fig. 4 presents an overview of the corresponding control.

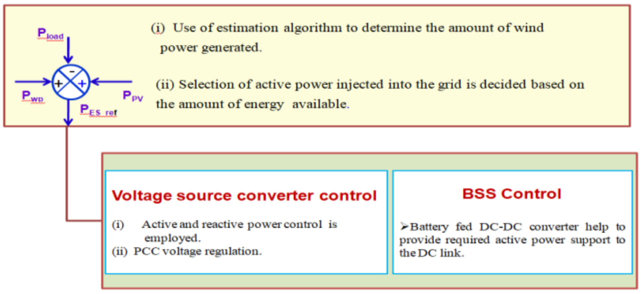



Figure 4: A VSC with dc-dc converter control

Based on the distribution network's load demand, the power outline of the systems for converting solar energy (SECS) and wind energy (WECS) is estimated at a high level for the next day, and (1) can be used to determine the actual power assistance from the energy storage (ES).

$$P_{ES}^{ref} = P_{wind} + P_{pv} + P_G - P_{Load} \quad (1)$$

The predicted capabilities of WECS and SECS for the next hour are indicated above, denoted as $P_{wp}$ and $P_{pv}$.The term "$P_{Load}$" describes the hourly load demand, whereas $P_G$ denotes the grid's scheduled power assistance in the absence of distributed generation. It is necessary to minimize variations in real power demand in energy-storage systems in order to manage the Common Coupling Point (CCP) voltage and deliver the voltage needed for the DC connection.

.

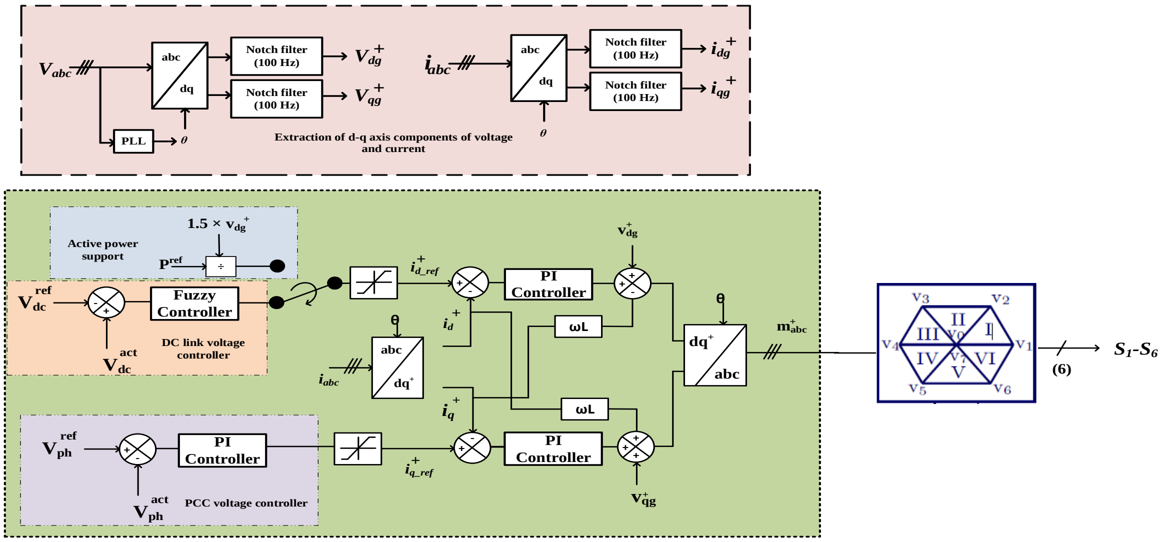



Figure 5 : Voltage source converter controller supporting grid codes

Later, it is run in P-$V_{ac}$ control mode to supply. Energy storage systems are essential for providing both active (actual) and reactive power assistance, which is necessary to stabilize voltage and frequency in the grid. The image makes it clear that, in accordance with the statement in (2), the DC-link voltage controller creates $i_{dref}$ first, the energy storage system delivers the necessary real power support after fulfilling the energy requirements.

$$I_d^{ref} = \frac{P_{ES}}{1.5 * V_d^*} \tag{2}$$

To provide the necessary $i_{qref}$ for voltage regulation, the PCC voltage controller makes sure that the appropriate reactive power is supplied.

In a similar manner, For CCP voltage regulation, reactive power is produced by $i_q$. The reference value of $i_q$ may be produced using (3). The reference for reactive power ($Q_{ES}$) in (3) comes from the controller's voltage control loop of CCP.

$$I_q^{ref} = -\frac{Q_{ES}}{1.5 * V_d^*} \tag{3}$$

In addition, the EsSt offers grid current balancing through negative sequence current compensation. The method described in [12] can be used to calculate the corresponding reference. However, it is never necessary for it to enable voltage regulation, correction for negative sequence current, and real/reactive power support.

## IV. FUZZY LOGIC CONTROLLER

Instead of using a typical PI controller at the dc-link voltage, a fuzzy logic controller should be employed. The fuzzyifier rule base, engine of inference, and defuzzyifier are the four main components of a System of fuzzy logic (SFL).Fuzzy variables are used when processing crisp inputs into crisp outputs by a fuzzy controller. The error $e_{dc}$ in this suggested control method is calculated as the difference between $V_{dc}$ and $V_{dc\_ref}$. The fuzzy controller produces fuzzy outputs by using the derivative of $e_{dc}$,or $Ce_{dc.}$

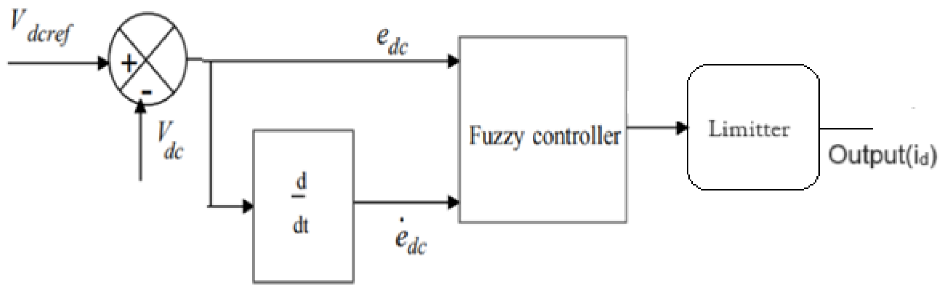
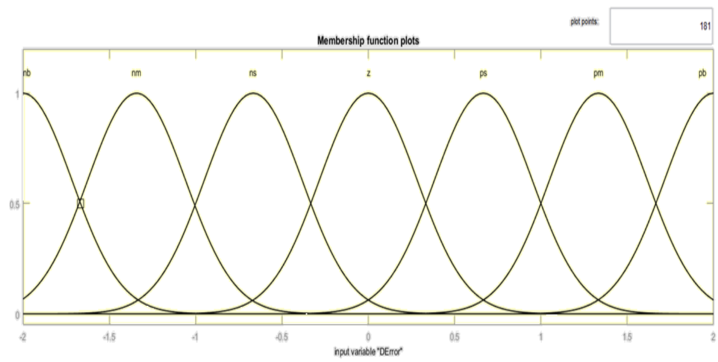


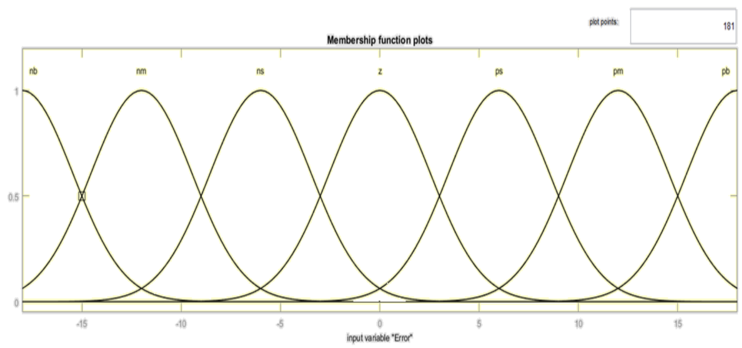

Figure:6 Control strategy of proposed fuzzy

Linguistic variables are used to quantify the signals into seven levels: Extremely High Positive (+EB), Positive yet Moderate (+M), Very small Positive (+VS), zero (Z), Very Large negative (-VB), Medium Negative (-M), and Very Small negative (-VS). Table.1 lists the 49 fuzzy rules that have been implemented into the proposed controllers. The fuzzy logic system's fundamental component is the rule base. It describes how the controller functions under various input conditions. A set of If-Then rules are used to build the rule foundation. Seven levels of quantization are also applied to the output signal id [16-17].

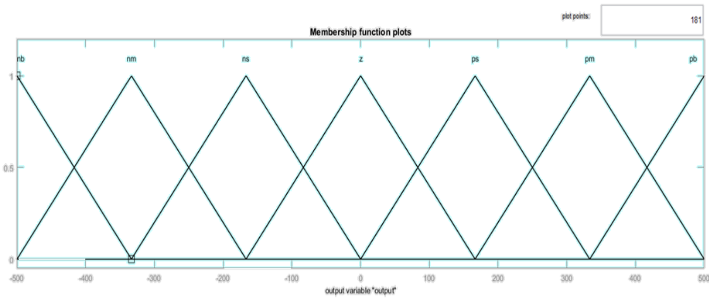
The outcome of this paper is triangle membership functions, which are mostly utilized because of their great computational and performance efficiency. The error (e) and change in error (ce) are Gaussian functions. For defuzzification [16-23].




(a)




(b)




(c)

Figure 7: (a) The input's membership functions error(e)  (b) Change in the membership function for error(ce)

(c) Functions of membership for output

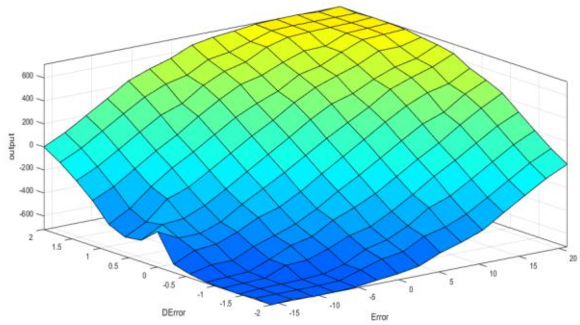



Figure 8: Layout of surface viewer

Table-1: DC Voltage Controller Using Fuzzy Logic Based on

| $E_{DC}/CE_{DC}$ | -EB | -M | -VS | Z | +VS | +M | +EB |
|---|---|---|---|---|---|---|---|
| -EB | -EB | -EB | -EB | -EB | -M | -VS | Z |
| -M | -EB | -EB | -EB | -M | -VS | Z | +VS |
| -VS | -EB | -EB | -M | -VS | Z | +VS | +M |
| Z | -EB | -M | -VS | Z | +VS | +M | +EB |
| +VS | -M | -VS | Z | +VS | +M | +EB | +EB |
| +M | -VS | Z | +VS | +M | +EB | +EB | +EB |
| +EB | Z | +VS | +M | +EB | +EB | +EB | +EB |

## V. DISCUSS ON SIMULATION RESULT

The improvement of VSC-based EsSt and controller parameter modification with a fuzzy logic controller and PI controller is shown in this section

### *A. VSC controller specifications*

The control technique for using the VSC to supply both reactive and actual power is shown in Fig. 5. According to the illustration, a synchronously rotating DQ frame is used to implement the controller. The required modulation index (m) is generated via complete control. It is possible to change the actual and reactive power Support within the VSC by varying the $i_d$ and $i_q$ components. The quantity of $i_{d\_ref}$ is determined by the Active Power Controller and DC-Link Voltage Controller. The initial step in obtaining the STATCOM features is controlling the $i_{d\_ref}$ to produce the discontinuous DC-link voltage ($V_{dc}$). "Active power controller" determines whether to supply actual power assistance after $V_{dc}$ reaches the desired value [12].

*B. DC-DC converter Control*

At the DC-link of the two level converter is the DC-DC converter that combinations the battery voltage. The matching schematic block diagram is displayed in Fig.5. Battery provides 350 kW of the support for overall active power.

$$P_b = i_b \times V_b \tag{4}$$

where $V_b$ and $i_b$ represent the battery bank's terminal voltage and current, respectively.

$$i_L = \frac{P_b}{V_b} \tag{5}$$

As shown in Fig. 9, the controller's current reference($i_L$) is derived using equation (5).

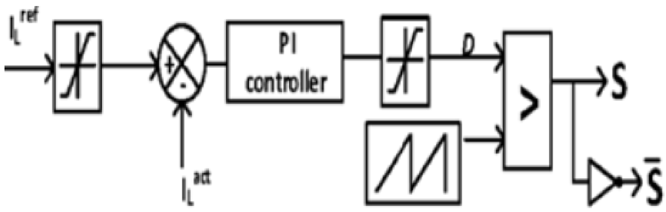



Figure 9: Battery-fed DC-DC converter control block diagram

The amount of active power produced by WEGS ($P_{wp}$) as a result of wind velocity fluctuation is displayed in Fig. 9, which also shows the amount of active power assistance provided by EsSt. The amount of reactive and active power is shown in Fig. 10. From the figure it is clear that the grid is receiving continuous active power. The reactive power required in order to keep the voltage at CCP. Fig.11. shows the performance of the dc-link voltage controller. The figure shows how, with the help of a fuzzy controller, the real dc-link voltage tracks the reference with no steady-state error

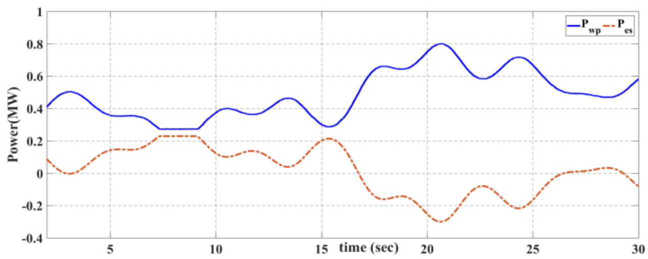



Figure 10: Active power generated by WEGS and power support from EsSt

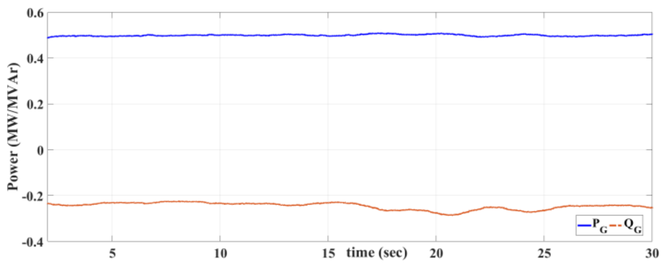



Figure 11: Active and reactive powers generated CCP

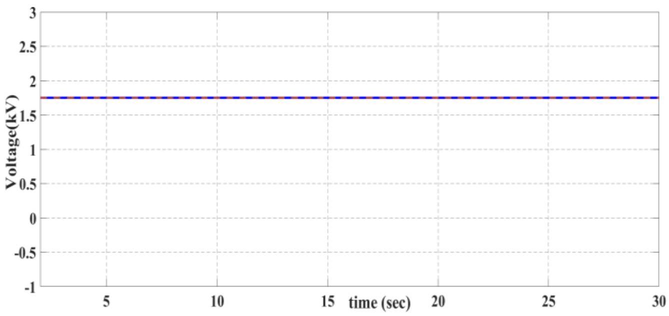



Figure 12: Reference and actual dc-link voltage

The following figures show the dynamic performance of the proposed fuzzy controller for controlling the dc-link voltage. During a step change, as shown in Fig. 12 and Fig.13, Typical PI controller performance is compared with that of the proposed controller. The time domain requirements for the voltage loop controller's step-response during the step rise of the dc-link voltage are displayed in table 2. A table 2 and 3 depicts the DC-DC converter's time domain requirements for a step adjustment to the reference voltage at output. The tables unequivocally demonstrate that the controller that applies fuzzy logic to the result of its parameter adjustments performs better than the other. The following tables show the time domain requirements for the step-response of the voltage loop controller of the DC-DC controller. The time domain requirements for a step adjustment in the DC-DC converter in the output reference voltage are shown in Tables 2 and 3. It is evident from the tables that the controller that has its parameters adjusted using fuzzy logic performs better than compared to the conventional PI controller.

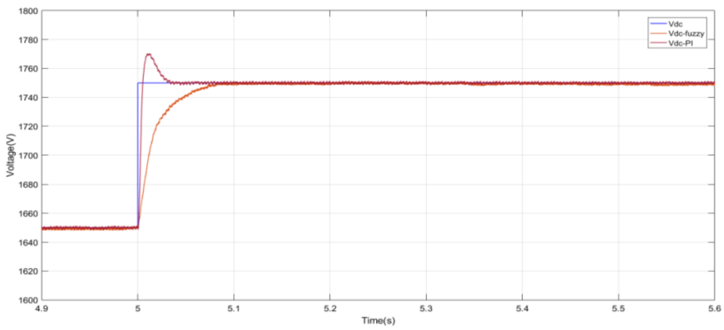



Figure 13: Variation of Dc-link voltage step increase

Table -2: Voltage loop controller time domain parameters for DC-DC step shift from 1650V to 1750V

| **Parameter** | **Value** | |
|---|---|---|
| | **PI controller** | **Fuzzy controller** |
| Peak overshoot(V) | 20% | 0 |
| Rise time ($t_r$) | 4ms | 48ms |
| Settling time ($t_s$) | 35ms | 62ms |

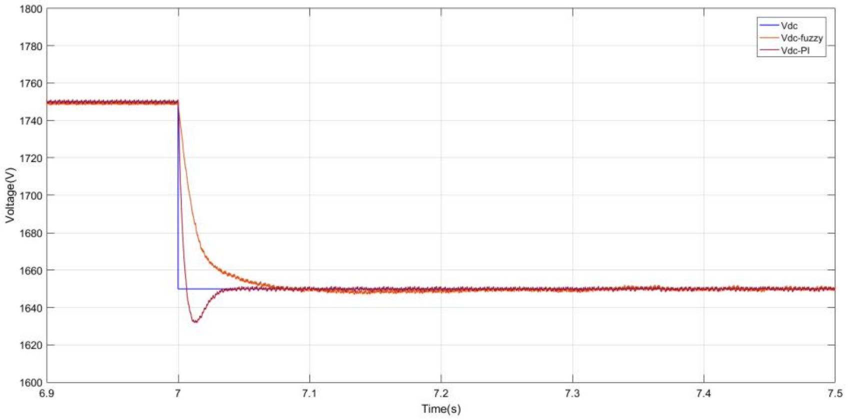



Figure 14:Variation of Dc-link voltage step decrease

Table- 3 Time domain parameters during Step decrease

| **Parameter** | **Value** | |
|---|---|---|
| | **PI controller** | **Fuzzy controller** |
| Peak overshoot(V) | 16% | 0 |
| Rise time ($t_r$) | 5ms | 32ms |
| Settling time ($_{ts}$) | 36ms | 74ms |

Table 4: Rating of the energy-storage device

| S.No. | Parameter | Value |
|---|---|---|
| 1 | The capacity of each battery module | 0.175 MWh |
| 2 | Battery modules provide active power support. | 0.35 MW |
| 3 | Nominal battery module's voltage | 1.35 kV |
| 4 | DC-DC converter's output voltage | 1.75kV |
| 5 | Duty ratio | 0.229 |
| 6 | Voltage of each battery | 3.5V |
| 7 | No.of series connected cell | 386 |
| 8 | Discharge current of each battery | 100A |
| 9 | No.of battery module in parallel | 3 |

| | | |
|---|---|---|
| 10 | A DC-DC converter's filter inductance | 14.82mH |
| 11 | Switching frequency | 1 kHz |

Table 5: Parameters of E-STATCOM

Table 6: Parameters of wind plant

| S.No. | Parameter | Value |
|---|---|---|
| 1 | Line voltage of the collecting bus | 11 kV |
| 2 | The SCIM's capacity | 1.5 MW |
| 3 | Rated voltage of SCIM | 590 V |
| 4 | MSC and GSC's capacity | 1.5 MW |

Table 7: Power injected into the grid

| S.No. | Parameter | Value |
|---|---|---|
| 1 | Injecting active power into the grid | 0.625MW |
| 2 | At PCC, reactive power support | 0.35 MVAr |
| 3 | Load at PCC | 100kVA,0.9 p.f |

## CONCLUSION

In this paper, It has been discussed how well an EsSt performs for an EDN that uses a battery storage device for production of renewable energy. In order to control the voltage at CCP and maintain a steady real power flow via the distribution transformer, the EsSt supplies the necessary real and reactive power. The battery was integrated using a half bridge-based bi-directional DC-DC conversion. The half-bridge dc-dc converter continuously maintains the dc-link voltage. P-$V_{AC}$ control is used by the two-level converter to support energy and manage the CCP voltage. As a result, the CCP has control over the voltage.

The simulation findings show that the PL controller suffers from the peak overshoot which reduces the life of the capacitor. In contrast, the proposed fuzzy controller eliminates the overshoot which improves the duration of the capacitor for the DC link. A comparison is presented between the suggested fuzzy controller for improved transient response and then PI controller. The results of the simulation show that by increasing the delay, the EsSt can minimize the overshoot and maintain a steady DC link voltage. Comparative analysis displays that the performance of fuzzy logic adjusted controllers is superior to that of PI controllers for DC voltage regulation by cutting out the overshoot. MATLAB/Simulink has been used to confirm the system's efficacy.

## REFERENCES

[1] Y. Ma, P. Yang and H. Guo, "Distributed generation system development based on various renewable energy resources," Proceedings of the 30th Chinese Control Conference, Yantai, China, 2011, pp. 6203-6207.

[2] J. M. Guerrero et al., "Distributed Generation: Toward a New Energy Paradigm," in IEEE Industrial Electronics Magazine, vol. 4, no. 1, pp. 52-64, March 2010, doi: 10.1109/MIE.2010.935862.

[3] G. W. Ault and J. R. McDonald, "Planning for distributed generation within distribution networks in restructured electricity markets," in IEEE Power Engineering Review, vol. 20, no. 2, pp. 52-54, Feb. 2000, doi: 10.1109/39.819919.

[4] Priyanka Chaudhary and M. Rizwan, “Voltage regulation mitigation techniques in distribution system with high PV penetration: A review” Renew. Sust. Ener. Rev., vol. 83, pp. 3279-3287, 2018. https://doi.org/10.1016/j.rser.2017.10.017.

[5] Sajad Jashfar and Saeid Esmaeili, “Volt/var/THD control in distribution networks considering reactive power capability of solar energy conversion,” Int. J. Electr. Power Energy Syst., vol. 60, pp. 221- 233, 2014, doi.org/10.1016/j.ijepes.2014.02.038.

[6] N.K. Roy, H.R. Pota and M.J. Hossain., " Reactive power management of distribution networks with wind generation for improving voltage stability.," Renew. Ener., vol. 58, no. 5, pp. 85-94, 2013, doi.org/10.1016/B978-0-323-85169-5.00005-8.

[7] Choton K. Das, Octavian Bass, Ganesh Kothapalli, Thair S. Mahmoud, and Daryoush Habibi, “Optimal placement of distributed energy storage systems in distribution networks using artificial bee colony algorithm,” App. Energy, vol. 232, pp. 212-228, 2018, https://doi.org/10.1016/j.apenergy.2018.07.100.

[8] Lim Khim Yan, Lim Yun Seng, Wong Jianhui and Chua Kein Huat, "Distributed energy storage with real and reactive power controller for power quality issues caused by renewable energy and electric vehicles," J. Energy Eng., vol. 142, no. 4, pp. 1-6, 2016,. 10.1061/(ASCE)EY.1943-7897.0000334.

[9] C. Roggatz, M. Power and N. Singh, "Power System Restoration: Meeting the Challenge to Resiliency from Distributed Generation," in IEEE Power and Energy Magazine, vol. 18, no. 4, pp. 31-40, July-Aug. 2020, doi: 10.1109/MPE.2020.2985438.

[10] N. R. Merritt, C. Chakraborty and P. Bajpai, "A control strategy for islanded operation of a Voltage Source Converter (VSC) based distributed resource unit under unbalanced conditions," 2015 IEEE 13th International Conference on Industrial Informatics (INDIN), Cambridge, UK, 2015, pp. 1550-1555, doi: 10.1109/INDIN.2015.7281964.

[11] A. Bharadwaj.Ch, S. Maiti, K. S. Krishna, N. Dhal, S. Chakraborty and S. K. Pillai, "Modular Multilevel Converter based STATCOM with Hybrid Energy Storage System Considering Unbalanced Loading Condition," 2020 IEEE 9th Power India International Conference (PIICON), Sonepat, India, 2020, pp. 1-6, doi: 10.1109/PIICON49524.2020.9113023.

[12] A. Bharadwaj, S. Maiti, N. Dhal and S. Chakraborty, "Control of Two Level Converter based STATCOM with Battery and Ultracapacitor," 2019 National Power Electronics Conference (NPEC), Tiruchirappalli, India, 2019, pp. 1-6, doi: 10.1109/NPEC47332.2019.9034874.

[13] J. C. Basilio and S. R. Matos, "Design of PI and PID controllers with transient performance specification," in IEEE Transactions on Education, vol. 45, no. 4, pp. 364-370, Nov. 2002, doi: 10.1109/TE.2002.804399.

[14] R. Ebrahimi, V. Eslampanah, H. M. Kojabadi, M. Azizian, N. N. Esfetanaj and D. Zhou, "A Robust Fuzzy-based Control Technique for Wind Farm Transient Voltage Stability Using SVC and STATCOM: Comparison Study," 2020 22nd European Conference on Power Electronics and Applications (EPE'20 ECCE Europe), Lyon, France, 2020, pp. P.1-P.5, doi: 10.23919/EPE20ECCEEurope43536.2020.9215750.

[15] A. F. Akkad, N. Erdili and E. Sosnina, "Application of a Fuzzy Logic Controller in a D-STATCOM in an Electrical Network with Distributed Generation," 2023 International Russian Smart Industry Conference (SmartIndustryCon), Sochi, Russian Federation, 2023, pp. 650-654, doi: 10.1109/SmartIndustryCon57312.2023.10110819.

[16] B. Singh and K. V. Srinivas, "Fuzzy logic control with constant dc link voltage of 48-pulse VSC based STATCOM," India International Conference on Power Electronics 2010 (IICPE2010), New Delhi, India, 2011, pp. 1-7, doi: 10.1109/IICPE.2011.5728125.

[17] J. Dalei, K. B. Mohanty, S. Singh and G. S. Garain, "Fuzzy PI controller for improved voltage regulation in STATCOM based SEIG," 2015 Annual IEEE India Conference (INDICON), New Delhi, India, 2015, pp. 1-5, doi: 10.1109/INDICON.2015.7443154.

[18] G. C. Konstantopoulos and A. T. Alexandridis, "Full-Scale Modeling, Control, and Analysis of Grid-Connected Wind Turbine Induction Generators With Back-to-Back AC/DC/AC Converters," in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 2, no. 4, pp. 739-748, Dec. 2014, doi: 10.1109/JESTPE.2014.2325676.

[19] A. Kalbat, "PSCAD simulation of grid-tied photovoltaic systems and Total Harmonic Distortion analysis," 2013 3rd International Conference on Electric Power and Energy Conversion Systems, Istanbul, Turkey, 2013, pp. 1-6, doi: 10.1109/EPECS.2013.6713002.

[20] V. Fernão Pires, Enrique Romero-Cadaval, D. Vinnikov, I. Roast and J.F. Martins., “Power converter interfaces for electrochemical energy storage systems– A review,” Energ. Convers. Manage., vol. 86., pp. 453-475, 2014. https://doi.org/10.1016/j.enconman.2014.05.003.

[21] Wang Zhifu, Wang Yupu and Rong Yinan, “Design of closed-loop control system for a bidirectional full bridge DC/DC converter,” App. Energy, vol. 194, pp. 617-625, 2017. doi.org/10.1016/j.apenergy.2016.11.113 .

[22] Huang, H.; Mao, C.; Lu, J.; Wang, D., " Small-signal modelling and analysis of wind turbine with direct drive permanent magnet synchronous generator connected to power grid," IET. Renew. Ener., vol. 6, no.1, pp. 48-58, 2012.doi:10.1049/IET-RPG.2010.0217.

[23] N. Kumar and Manisha, "A fuzzy integrated virtual synchronous machine based STATCOM replicating synchronous condenser," *2021 8th International Conference on Signal Processing and Integrated Networks (SPIN)*, Noida, India, 2021, pp. 270-275, doi: 10.1109/SPIN52536.2021.9566137