P-Q THEORY BASED UPQC FOR REACTIVE POWER COMPENSATION WITH UCAP

K.C.SANDHYA[1], B. SUGAD SINGH[2]

[1]II YEAR, POWER ELECTRONICS AND DRIVES, Bethlahem Institute of Engineering,Karungal-629157.
[2]Assistant professor, Department of Electrical and Electronics Engineering. Bethlahem Institute of Engineering,Karungal-629157.

***

Abstract - *This paper proposes a p-q theory based control of ulltracapacitor integrated unified power quality conditioner (UCAP-UPQC-S). The Ultracapacitors (UCAP) have low-energy density and high-power density ideal characteristics for compensation. The fundamental frequency positive sequence (FFPS) voltages are extracted using generalized cascaded delay signal cancellation (GCDSC) which is used in p- q theory based control to generate reference grid currents for the shunt compensator. The unified power quality controller (UPQC) operating in voltage control mode. The reference stator current is generated by using P-Q theory. The ultracapacitor (UCAP) integrated at the DC-bus of the UPQC, provides a part of active load power. The series VSC operates such that it shares a part of the reactive power of the load even under nominal grid conditions. The dynamic performance of proposed system is verified by simulating it in Matlab-Simulink using a combination of linear and non-linear load.*

Key Words: Power quality, UPQC, UCAP, p-q theory, Series compensation, Shunt compensation.

1. INTRODUCTION

There is an increasing need for renewable energy systems (RES) with ancillary features particularly in low voltage distribution systems. Ancillary features include harmonic compensation, reactive power compensation, low voltage ride through capability etc. This is due to the fact that there is increased penetration of nonlinear power electronics based loads[1]. These loads inject harmonic currents into grid which can cause distortion at point of conunon coupling (PCC) particularly in weak grid systems. Moreover, due to the intermittent nature of the clean energy sources such as wind and solar energy, their increased penetration lead grid voltage fluctuations depending upon power generation and demand. These voltage fluctuations can affect sensitive power electronic loads such as adjustable speed drives, lighting systems etc which can lead to frequent tripping, maloperation and thus leading to increased maintenance costs. Renewable energy integration with power quality enhancing sytems such as dynamic voltage restorer (DVR), unified power quality conditioner (UPQC) and distribution static compensator (DSTATCOM) provides an ideal solution by combining benefits of clean energy with power quality enhancement. DSTATCOM [2] is a shunt VSC which for load power quality issues such as current harmonics, load reactive power, unbalance etc. DVR[3] is a series VSC which protects sensitive loads against grid voltage disturbances such as sags/swells, flicker interruption etc. UPQC is a versatile device as it compensates for both load side and grid side power quality problems. A detailed review of various UPQC configurations and control has been given in [4]. The series VSC of UPQC comes into operation under grid voltage sags/swells, flicker and unbalance which are short duration variations. Compared with shunt VSC which compensator, the series VSC utilization is much lesser. Two major trends in UPQC are to increase the utilization of series inverter[5] and integration of distribution generation system particularly UCAP at the DC-bus of UPQC[6]. The most commonly used algorithms for reference signal generation are based in time domain. These include pq theory [7], d-q theory [3] and instantaneous symmetrical components theory. Some other advanced control techniques for reference signal generation include using adaptive filters such as adaptive notch filter [8], ADALINE [9] etc. However, these methods require calculations for each phase currents and voltages and are more complex compared to methods based on p-q or d-q theory which are inherently three-phase based techniques. Though the classical p-q theory involves only simple calculations, it doesn't produce accurate results under conditions of voltage distortions or unbalance [10]. This drawback can be overcome by using fundamental frequency positive sequence (FFPS) voltages for generating reference currents using p-q theory. Modified p-q theory using phase locked loop (PLL) was proposed in [11]. The various other methods to extract fundamental frequency positive sequence voltages are using notch filters [12], generalized cascaded delay signal cancellation (GCDSC) based methods [l3] etc This paper proposes control of UCAP-UPQC by modified p-q theory based technique wherein the fundamental positive sequence voltages are extracted using GCDSC method. The shunt VSC compensates for part of load reactive power and also injects real power obtained from the SPY array into grid. The reference voltage for the DC bus is obtained from maximum power point tracking (MPPT) algorithm [14]. The series converter operates such that a part of reactive load power is shared by the series converter under sag and normal operating conditions thus reducing VA loading on the shunt VSc. The system is simulated using Matlab-Simulink and its dynamic performance is tested under conditions of irradiation variation, voltage sags/swells, distortions etc.

II.CONFIGURATION OF UCAP-UPQC

The topology of a UCAP-UPQC is presented in Fig.I. The major parts of the system are a series VSC and shunt VSC connected back to back through a common DC-bus. The VSCs are connected to grid using interfacing inductors. Ripple filters are used to filter out switching harmonics of the VSCs. The series VSC injects voltage through a series injection transformer. The SPY array is connected directly at the DC bus of UPQC through a reverse blocking diode.

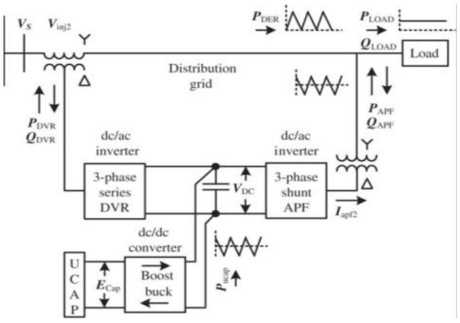

Fig.1. One line diagram of UCAP-UPQC.

In this paper, UCAP-based energy storage integration through a power conditioner into the distribution grid is proposed, and the following application areas are addressed.

1) Integration of the UCAP with power conditioner system gives the system active power capability.
2) Active power capability is necessary for independently compensating voltage sags/swells and to provide active/reactive power support and intermittency smoothing to the grid.
3) Experimental validation of the UCAP, dc–dc converter, inverter their interface, and control.
4) Development of inverter and dc–dc converter controls to provide sag/swell compensation and active/reactive support to the distribution grid.
5) Hardware integration and performance validation of the integrated UCAP-PC system.

III.THREE-PHASE SERIES INVERTER

A.POWER STAGE

The one-line diagram of the system is shown in Fig. 1. The power stage is a three-phase voltage source inverter, which is connected in series to the grid and is responsible for compensating the voltage sags and swells; the model of the series DVR and its controller is shown in Fig. 2. The inverter system consists of an insulated gate bipolar transistor (IGBT) module, its gate-driver, LC filter, and an isolation transformer. The dc-link voltage Vdc is regulated at 260 V for optimum performance of the converter and the line–line voltage Vab is 208 V; based on these, the modulation index m of the inverter is given by

$$m=2\sqrt{2}\sqrt{3}Vdc*nVab(rms). \quad (1)$$

where n is the turns ratio of the isolation transformer. Substituting n as 2.5 in (1), the required modulation index is calculated as 0.52. Therefore, the output of the dc–dc converter should be regulated at 260 V for providing accurate voltage compensation. The objective of the integrated UCAPDVR system with active power capability is to compensate for temporary voltage sag (0.1–0.9 p.u.) and voltage swell (1.1–1.2 p.u.), which last from 3 s to 1 min [15].

B.CONTROLLER IMPLEMENTATION

There are various methods to control the series inverter to provide dynamic voltage restoration and most of them rely on injecting a voltage in quadrature with advanced phase, so that reactive power is utilized in voltage restoration [3]. Phase advanced voltage restoration techniques are complex in implementation, but the primary reason for using these techniques is to minimize the active power support and thereby the amount of energy storage requirement at the dc-link in order to minimize the cost of energy storage. However, the cost of energy storage has been declining and with the availability of active power support at the dc-link, complicated phase-advanced techniques can be avoided and voltages can be injected in-phase with the system voltage during a voltage sag or a swell event. The control method requires the use of a PLL to find the rotating angle. As discussed previously, the goal of this project is to use the active power capability of the UCAP-DVR system and compensate temporary voltage sags and swells.

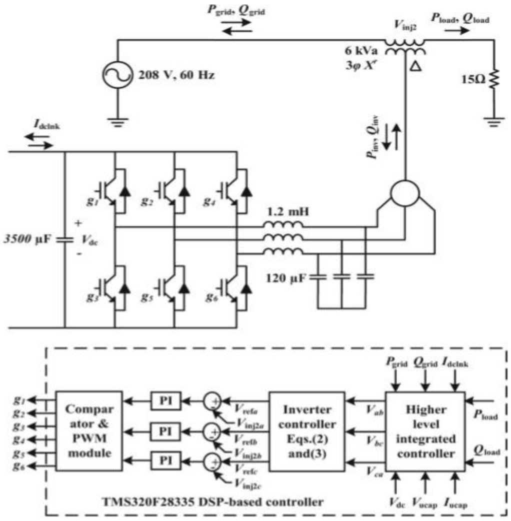

Fig.2. Model of three-phase series inverter (DVR) and its controller with integrated higher order controller.

IV. UCAP AND BIDIRECTIONAL DC–DC CONVERTER

A.UCAP BANK HARDWARE SETUP

UCAPs can deliver very high power in a short time span; they have higher power density and lower energy density when compared with Li-ion batteries [18], [19]. The major advantage UCAPs have over batteries is their power density characteristics, high number of charge–discharge cycles over their lifetime, and higher terminal voltage per module [5], [18]. These are ideal characteristics for providing active/reactive power support and intermittency smoothing to the distribution grid on a short-term basis. In [20], it is proposed that UCAPs are currently viable as short-term energy storage for bridging power in kilowatt range in the seconds to few minutes timescale. The choice of the number of UCAPs necessary for providing grid support depends on the amount of support needed, terminal voltage of the UCAP, dc-link voltage, and distribution grid voltages. For a 260-V dc-link voltage, it is practical and cost-effective to use three modules in the UCAP bank. Therefore, in this paper, the experimental setup consists of three 48 V, 165 F UCAPs (BMOD0165P048) manufactured by Maxwell Technologies, which are connected in series.

B.BIRECTIONAL DC-DC CONVERTER

A bidirectional dc–dc converter is required as an interface between the UCAP and the dc-link, since the UCAP voltage varies with the amount of energy discharged, while the dc-link voltage has to be stiff. The model of the bidirectional dc–dc converter and its controller are shown in Fig. 4(a). The dc–dc converter should operate in Discharge mode, while providing active/reactive power support and voltage sag compensation.

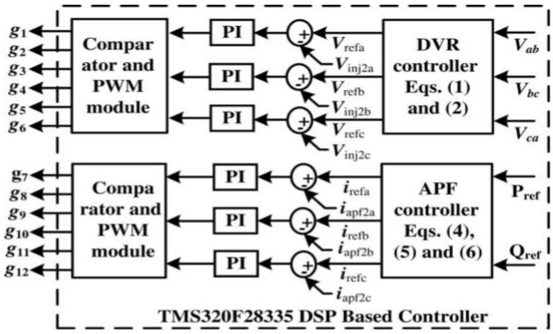

Fig.3. Controller block diagram for DVR and APF.

The dc–dc converter should also be able to operate in bidirectional mode to be able to charge or absorb additional power from the grid during intermittency smoothing. In this paper, the bidirectional dc–dc converter acts as a boost converter, while discharging power from the UCAP and acts as a buck converter while charging the UCAP from the grid. Average current mode control, which is widely explored in literature [19], is used to regulate the output voltage of the bidirectional dc–dc converter in both Buck and Boost modes while charging and discharging the UCAP bank. This method tends to be more stable when compared with other methods like voltage mode control and peak current mode control. Average current mode controller is shown in Fig. 3, where the actual output voltage Vout is compared with the reference voltage Vref and the error is passed through the voltage compensator C1 (s) that generates the average reference current Iucref.

C. CONTROLLER IMPLEMENTATION

Average current mode control is used to regulate the output voltage of the bidirectional dc–dc converter in both Buck and Boost modes, while charging and discharging the UCAP bank. While the UCAP-APF system is discharging power, the dc-link voltage Vout tends to be less than Vref, which causes the reference current Iucref to be positive, thereby operating the dc–dc converter in Boost mode. Along similar lines, when the UCAP-APF system is absorbing power from the grid, the dc-link voltage Vout tends to be greater than Vref, which causes the reference current Iucref to be negative and thereby operating the dc–dc converter in Buck mode. Average current mode control technique is widely explored in the literature [19], and it was found as the ideal method for UCAP-APF integration as it tends to be more stable when compared with other methods like voltage mode control and peak current mode control. This is a major advantage in the present topology, where the stability of the dc–dc converter has to be ensured over a wide operating range and in both Buck and Boost modes of operation. Average current mode controller and the higher level integrated controller are shown in Fig. 4(a), where the actual output voltage Vout is compared with the reference voltage Vref and the error is passed through the voltage compensator C1 (s), which generates the average reference current Iucref. This is then compared with the actual UCAP current (which is also the inductor current) Iuc, and the error is then passed through the current compensator C2 (s).

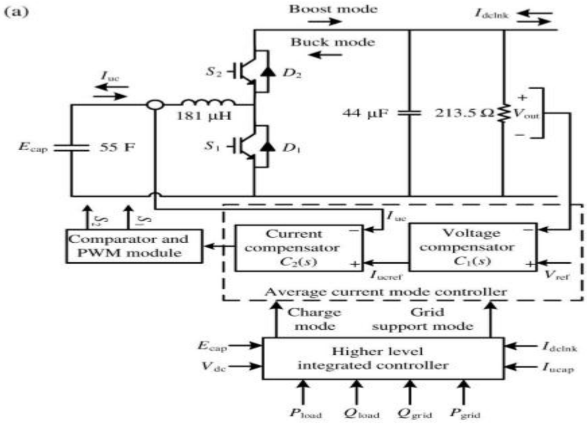

Fig.4. (a) Model of the bidirectional dc–dc converter and its controller.

D. HIGHER LEVEL INTEGRATED CONTROLLER

The higher level integrated controller is designed to make system level decisions on the inverter and dc–dc converter controllers. Based on various system parameters like Pload, Qload, Pgrid, Qgrid, Vucap, Vdc, Idclnk, and Iucap, the higher level integrated controller will decide on operating in one of the following modes: active power support mode, reactive power support mode, renewable intermittency smoothing mode, sag/swell compensation mode, and UCAP charge mode. In active power support mode and renewable intermittency smoothing mode, the UCAP-PC system must provide active power to the grid. Therefore, the active power capability of the UCAP-PC system must be assessed by the higher level integrated controller. Based on the Pgrid and Pload values, the reference Pref is calculated in the higher level integrated controller, and it will decide if the UCAP has enough energy to respond to the Pref command based on the UCAP state of charge. If the UCAP has enough capacity to respond to the request, then the dc–dc converter controller is operated in grid support mode; otherwise, it is operated in charge mode, where the UCAP is recharged and the power request is met at a later time. In grid support mode, the dc–dc converter will operate in a bidirectional fashion in both Buck and Boost modes to respond to the active power requests and regulate the dc-link voltage in a stable fashion, while the inverter controller should respond such that the commanded Pref is supplied by the inverter through current control. In reactive power support mode, the UCAP-PC system must provide reactive power to the grid. In this mode, the UCAP-PC does not provide any active power to the grid and even the PC losses are supplied by the grid. Based on the Qgrid and Qload values, the reference Qref is calculated in the higher level integrated controller. In this mode, the dc–dc converter controller can be programmed to operate in grid support mode directly because the active power requirement for operating in this mode is minimal. Therefore, the goal of the dc–dc converter controller is to regulate the dc-link voltage in a stable fashion, while the inverter controller should respond such that the commanded Qref is supplied by the inverter through current control. In sag/swell compensation mode, the UCAP-PC system is programmed to prevent sensitive loads from disturbances on the supply-side like voltage sag or voltage swell. These disturbances require short-term energy storage, and in this mode, the dc–dc converter controller can be programmed to operate in grid support mode. Therefore, the goal of the dc–dc converter controller is to regulate the dc-link voltage in a stable fashion during both sag/swell events. It is also required that the dc–dc converter be able to discharge and meet the active power requirements during a voltage sag and to be able absorb active power in a stable fashion during a voltage swell event. In charge mode, the UCAP is recharged by absorbing active power from the grid when the UCAP state of charge falls below 50%. The rate at which the UCAP can be charged is assessed by the higher level integrated controller based on the Pgrid and Pload values and the reference Pref is calculated. Then the dc–dc converter controller is commanded to operate in charge mode, wherein the dc–dc converter will operate in Buck Mode to absorb the power from the grid and the inverter controller must respond to supply commanded Pref.

IV.SIMULATION RESULTS

The simulation of the proposed UCAP integrated power conditioner system is carried out in Matlab for a 208-V, 60-Hz system, where 208 V is 1 p.u. The system response for a three-phase voltage sag which lasts for 0.1 s and has a depth of 0.64 p.u. It can be observed that during voltage sag, the source voltage Vsrms is reduced to 0.36 p.u., while the load voltage VLrms is maintained constant at around 1.01 p.u. due to voltages injected in-phase by the series inverter. This can also be observed from the plots of the line–line source voltages (Vsab, Vsbc, and Vsca) ,the line–line load voltages (VLab, VLbc, and VLca) ,and the line–neutral injected voltages of the series inverter (Vinj2a, Vinj2b, and Vinj2c) . The active power deficit of the grid is met by the DVR power Pdvr, which is almost equal to the input power to the inverter Pdc in available from the UCAP. Therefore, it can be concluded from the plots that the active power deficit between the grid and load during the voltage sag event is being met by the UCAP-based energy storage system through bidirectional dc–dc converter and the inverter. It can also be noticed that the grid reactive power Qgrid reduces during the voltage sag while Qdvr increases to compensate for the reactive power loss in the system. Similar analysis can also be carried out for voltage sags that occur in one of the phases (A, B, or C) or in two of the phases (AB, BC, or CA); however, three-phase voltage sag case requires the maximum active power support and is presented here. The proposed UCAP integrated power conditioner system's performance is then simulated for the active and reactive power support case.

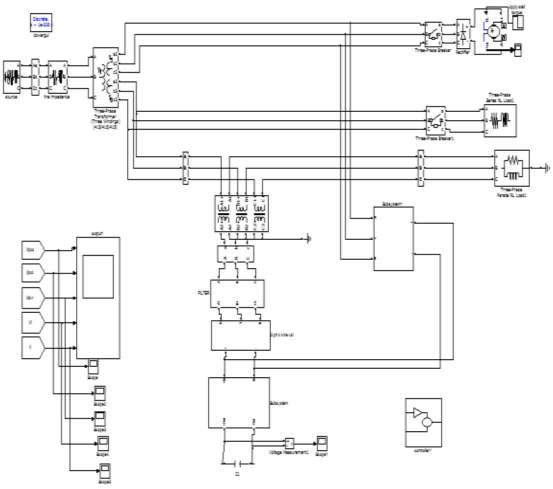

Fig.5. MATLAB/SIMULINK UPQC with UCAP.

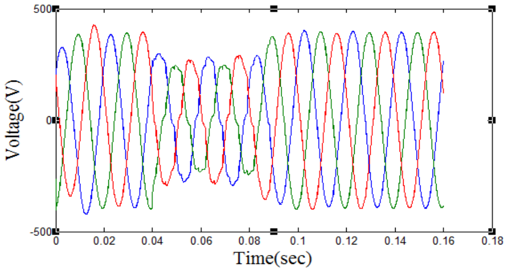

Fig.6. Source voltage.

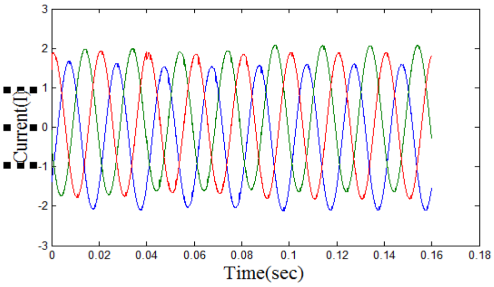

Fig.7. Source current.

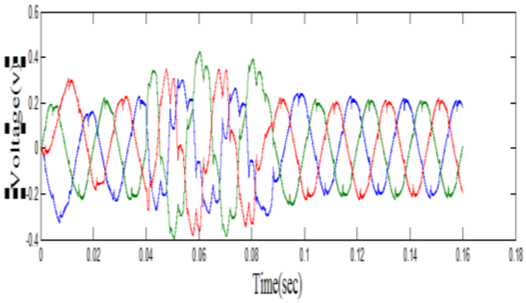

Fig.8. DVR voltage.

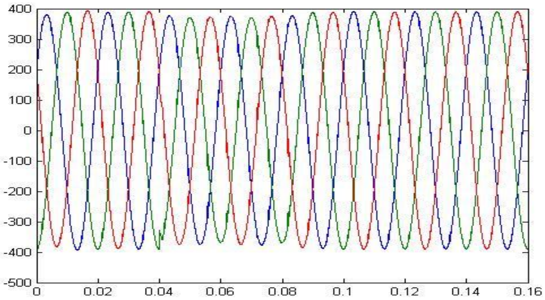

Fig.9. Load voltage.

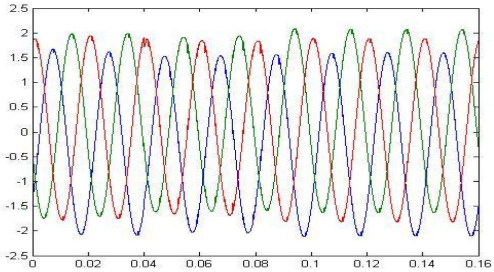

Fig.10. Load current.

VI. CONCLUSION

In this paper, the concept of integrating UCAP-based rechargeable energy storage to a power conditioner system to improve the power quality of the distribution grid is presented. With this integration, the DVR portion of the power conditioner will be able to independently compensate voltage sags and swells and the APF portion of the power conditioner will be able to provide active/reactive power support and renewable intermittency smoothing to the distribution grid. UCAP integration through a bidirectional dc–dc converter at the dc-link of the power conditioner is proposed. The control strategy of the series inverter (DVR) is based on inphase compensation and the control strategy of the shunt inverter (APF) is based on id −iq method. Designs of major components in the power stage of the bidirectional dc–dc converter are discussed. Average current mode control is used to regulate the output voltage of the dc–dc converterdue to its inherently stable characteristic. A higher level integrated controller that takes decisions based on the system parameters provides inputs to the inverters and dc–dc converter controllers to carry out their control actions. The simulation of the integrated UCAP-PC system which consists of the UCAP, bidirectional dc–dc converter, and the series and shunt inverters is carried out using PSCAD. The simulation of the UCAP-PC system is carried out using PSCAD. Hardware experimental setup of the integrated system is presented and the ability to provide temporary voltage sag compensation and active/reactive power support and renewable intermittency smoothing to the distribution grid is tested. Results from simulation and experiment agree well with each other thereby verifying the concepts introduced in this paper. Similar UCAPbased energy storages can be deployed in the future in a microgrid or a low-voltage distribution grid to respond to dynamic changes in the voltage profiles and power profiles on the distribution grid.

ACKNOWLEDGEMENT

The authors would like to express a gratitude especially to Ms.K.Christal saji.,Associate professor and Head of the Department for the invaluable advice and support that she has given to the authors.

REFERENCES

[1] N. H. Woodley, L. Morgan, and A. Sundaram, "Experience with an inverter-based dynamic voltage restorer," IEEE Trans. Power Del., vol. 14, no. 3, pp. 1181–1186, Jul. 1999.

[2] J. G. Nielsen, M. Newman, H. Nielsen, and F. Blaabjerg, "Control and testing of a dynamic voltage restorer (DVR) at medium voltage level," IEEE Trans. Power Electron., vol. 19, no. 3, pp. 806–813, May 2004.

[3] V. Soares, P. Verdelho, and G. D. Marques, "An instantaneous active and reactive current component method for active filters," IEEE Trans. Power Electron., vol. 15, no. 4, pp. 660–669, Jul. 2000.

[4] H. Akagi, E. H. Watanabe, and M. Aredes, Instantaneous Reactive Power Theory and Applications to Power Conditioning, 1st ed. Hoboken, NJ, USA: Wiley/IEEE Press, 2007.

[5] K. Sahay and B. Dwivedi, "Supercapacitors energy storage system for power quality improvement: An overview," J. Energy Sources, vol. 10, no. 10, pp. 1–8, 2009.

[6] B. M. Han and B. Bae, "Unified power quality conditioner with super-capacitor for energy storage," Eur. Trans. Elect. Power, vol. 18, pp. 327–343, Apr. 2007.

[7] P. F. Ribeiro, B. K. Johnson, M. L. Crow, A. Arsoy, and Y. Liu, "Energy storage systems for advanced power applications," Proc. IEEE, vol. 89, no. 12, pp. 1744–1756, Dec. 2001.

[8] A. B. Arsoy, Y. Liu, P. F. Ribeiro, and F. Wang, "StatCom-SMES," IEEE Ind. Appl. Mag., vol. 9, no. 2, pp. 21–28, Mar. 2003.

[9] J. Rittershausen and M. McDonagh, Moving Energy Storage from Concept to Reality: Southern California Edison's Approach to Evaluating Energy Storage [Online].

[10] M. Branda, H. Johal, and L. Ion, "Energy storage for LV grid support in Australia," in Proc. IEEE Innov. Smart Grid Tech. Asia (ISGT), Nov. 13–16, 2011, pp. 1–8.

[11] W. Li, G. Joos, and J. Belanger, "Real-time simulation of a wind turbine generator coupled with a battery supercapacitor energy storage system," IEEE Trans. Ind. Electron., vol. 57, no. 4, pp. 1137–1145, Apr. 2010.

[12] P. Thounthong, A. Luksanasakul, P. Koseeyaporn, and B. Davat, "Intelligent model-based control of a standalone photovoltaic/fuel cell power plant with supercapacitor energy storage," IEEE Trans. Sustain. Energy, vol. 4, no. 1, pp. 240–249, Jan. 2013.

[13] X. Li, D. Hui, and X. Lai, "Battery energy storage station (BESS)-based smoothing control of photovoltaic (PV) and wind power generation fluctuations," IEEE Trans. Sustain. Energy, vol. 4, no. 2, pp. 464–473, Apr. 2013.

[14] J. Tant, F. Geth, D. Six, P. Tant, and J. Driesen, "Multiobjective battery storage to improve PV integration in residential distribution grids," IEEE Trans. Sustain. Energy, vol. 4, no. 1, pp. 182–191, Jan. 2013.

[15] Y. Ru, J. Kleissl, and S. Martinez, "Storage size determination for gridconnected photovoltaic systems," IEEE Trans. Sustain. Energy, vol. 4, no. 1, pp. 68–81, Jan. 2013.

[16] S. Teleke, M. E. Baran, S. Bhattacharya, and A. Q. Huang, "Rule-based control of battery energy storage for dispatching intermittent renewable sources," IEEE Trans. Sustain. Energy, vol. 1, no. 3, pp. 117–124, Oct. 2010.

[17] T. K. A. Brekken et al., "Optimal energy storage sizing and control for wind power applications," IEEE Trans. Sustain. Energy, vol. 2, no. 1, pp. 69–77, Jan. 2011.

[18] S. Santoso, M. F. McGranaghan, R. C. Dugan, and H. W. Beaty, Electrical Power Systems Quality, 3rd ed. New York, NY, USA: McGraw-Hill, Jan. 2012.

[19] R. W. Erickson and D. Maksimovic, Fundamentals of Power Electronics, 2nd ed. Norwell, MA, USA: Kluwer, 2001.

K.C.SANDHYA received her B.E degree in Electrical and electronics Engineering in 2015 from Sun college of Engineering and Technology, Now studying M.E Power Electronics and drives in Bethlahem Institute of Engineering.

B.SUGAD SINGH received his B.E degree in Electrical and Electronics Engineering and M.E degree in Power Electronics and Drives from anna university, Chennai. At present working as an assistant professor in the department of Electrical and Electronics Engineering, Bethlahem institute of Engineering. His area of interest includes Machines and Power Electronics.