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Regular paper

Stabilized Power Management in the Microgrid Using Unified Delta Controller

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The idea of reducing the transmission losses and encouraging the pollution free energy generation has increased the demand for microgrid systems throughout the world in the recent years. However, optimal utilization of sources along with overcoming the stability related issues in the MG system are to be taken care of. To address these issues, the state of art has presented various power management strategies and complex control techniques. In this regard, this paper aims to propose a novel delta based Controller for power management in the MG system comprising solar, wind battery along with DC and AC loads. Further, the proposed controller is also responsible for monitoring power stability and regulates DC and AC bus voltages in the MG system. This paper also proposes a transformer based MLI (TBMLI) whose secondary produces HVs and LVs simultaneously. The analysis of the TBMLI has been presented. The proposed δ-Controller has been validated for source and load intermittencies in the MATLAB/Simulink environment.

Keywords: **Transformer based MLI (TBMLI), δ- Delta Controller, MPPT**

I. INTRODUCTION

The demand for clean energy with the increased concern for pollution and decrease in fossil fuels has coerced human to switch to renewable sources for meeting the electrical energy demand. The world has witnessed a tremendous growth in the employability and technological advancements in the field of renewable sources especially in the last decade [1]. In a developing country like India, distributed generation (DG) serves a crucial role for electricity generation in isolated locations. The DGs in general are set up with a hybrid microgrid employing renewable sources especially solar and wind. The battery and diesel generator are employed as back up to ensure reliability of the system [2]. The general architecture of microgrid with Solar and wind as primary sources and battery as auxiliary source employed for Hybrid AC/DC microgrid is depicted in Fig.1. The major equipment involved includes the RES with respective converters for voltage regulation at the DC link, inverter for DC-AC conversion, filter followed by the loads connected to the PCC and then to the utility grid with a transformer. This structure is well established and is in common practice. However, the major limitations include high filter requirements and simple power management strategy. To address this issue of high filter requirements, conventional H-bridge inverters are replaced by multilevel inverters.

Unlike normal conventional inverters, multilevel inverters generate high quality output voltage waveform as well as a less distorted input current wave shape. The other features include less total harmonic distortion, large power conversion capability, low dv/dt stress on switches, lower switching losses, reduced EMI, lower switching losses and smaller

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common mode voltage. They can also operate at both higher switching frequencies and fundamental switching frequency according to the applications [3].

The major challenge in microgrid is power management among the sources [4]. The prime objective of the power management strategy is to regulate the voltage and frequency variations and optimal dispatching of power among the available RES in microgrid [5]. The control system and the power management strategy developed in [6] focus on the inverter side and has no control on the reactive power flow. A control method discussed in [7] for a PV-wind-battery system focus on optimizing size and cost of the battery and PV array. However, the dynamic power balancing has been ignored. Also, requires huge historical data of past 30 years for estimation of power generated by the wind turbine and the PV array. The scheme for hybrid PV-battery microgrid discussed in [8] presents a unified control and power management strategy. This strategy stably regulates the bus voltages and frequency, automatically balances the power flow in the system irrespective of the intermittencies on source and load end. An energy management strategy for microgrid in [9] employs neural network for optimal power flow among the sources in the microgrid. The novel droop control enabled with GPS discussed in [10] ensures autonomous operation of the sources. However, the accuracy of GPS may not be ensured. In [11], an adaptive dynamic power control strategy for PV array and charging/ discharging of super capacitor bank has been presented. However, external resistive dump loads are used to stabilize the dc-link when excess power is generated which results in power loss at times. A distributed power management strategy (DPMS) for a multi-paralleled bidirectional interlinking converters in a hybrid AC/DC microgrid with localized distributed controllers for communication exchange has been discussed in [12]. Due to localized controllers, the synchronization of the controllers becomes challenging and also requires more number of local controllers. This necessitates a simple controller for power management among the RES in microgrid.

Further, the other major challenge in microgrid (MG) is the power quality issue. Power quality issue can be defined as “any critical issue observed in current, voltage or frequency that results in deterioration of consumers’ equipment” [13]. This issue is a critical concern especially due to the presence of power electronic converters associated with RES in microgrid [14], [15]. The effective integration of RES and energy storage units has been a recommended solution for improving the power quality [16], [17]. However, the inverters employed in different applications induce non linearity in the system resulting in distorted waveform of the supply voltage which further leads to load failure. Hence, a proper design of inverter and power imbalances needs to be taken care of. To address this issue, a transformer based MLI (TBMLI) has been presented in [18]. Since the topology employs common core transformer, very high short circuit current flows from the source during short circuit of any of the winding.

To summarize, the conventional hybrid DC/AC microgrid suffers from one or the other limitations: high filter requirement, adopting more controllers for efficient power management and/or employing inverters resulting in power quality issues. In this regard, a transformer based MLI has been proposed in this paper to address the power quality issues. Further, to reduce the number of controllers, a delta (δ) based controller is proposed for power management in the MG. Moreover, the delta based controller also improves the voltage stability of the system. The other major contributions include:

- Development of multi winding transformer based MLI
- Providing low voltage and high voltage AC bus simultaneously.
- Development of δ-based controller for power management among the sources used in microgrid
- Improving the voltage stability using the same δ-based Controller technique

- Maintaining state of health of the battery using the same δ method

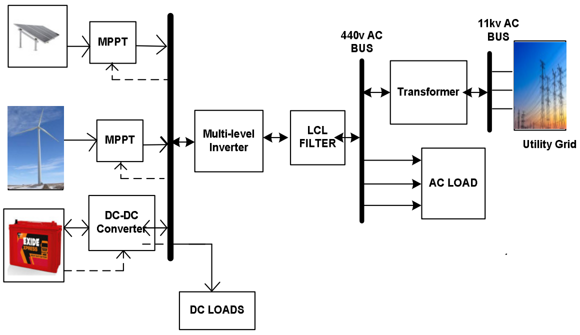


Fig.1. General Architecture of microgrid

II. PROPOSED MICROGRID

The proposed hybrid microgrid system depicted in fig.2 consist PV, wind, battery as energy sources and DC and AC loads and AC grid integrated to the DC bus along with the respective converters. The PV array of is interfaced with the DC bus by a boost converter which always make the array to operate at MPPT. The wind energy source is interfaced with DC bus by a rectifier. A bidirectional converter with effective charge discharge algorithm is employed to interface the battery bank. On the other hand, a new transformer based multi-level inverter is employed to convert DC to low voltage and High voltage AC and connect them to LV and HV AC buses respectively. The HV bus is connected to utility grid where as LV bus feeds the local AC loads. The DC loads are connected from the DC bus through the respective DC-DC converters. In conventional microgrid systems high gain DC-DC converters are used to feed the local DC loads so as to meet the AC bus requirements with conventional MLI i.e. DC bus needs to maintain high voltage. In the proposed MG system, due to usage of TBMLI which can generate both HV and LV AC with low DC, the DC bus voltage can be maintained at lower value when compared to conventional MG systems. This aids in using low gain DC-DC converters for feeding DC loads, which results in reducing the component count of DC-DC converters there by reducing the size, cost and weight of the system which increases efficiency and reliability of overall system.

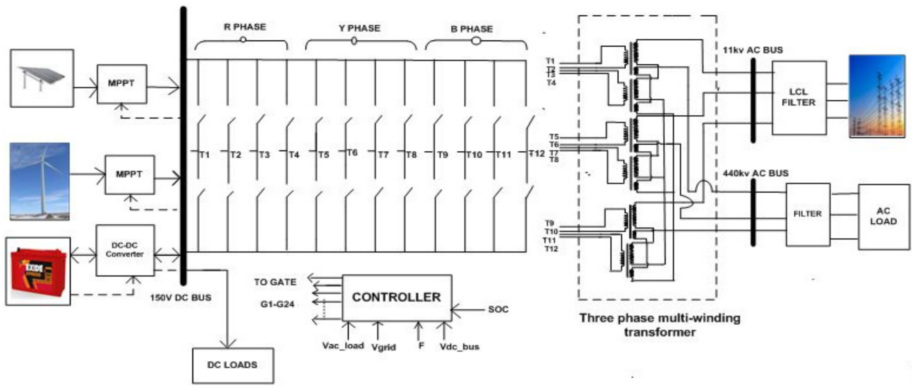


Fig.2. Proposed hybrid microgrid system

1) PROPOSED MLI

The proposed TBMLI for single phase is shown in fig.3. The proposed TBMLI generates 9 level phase voltages (both HV and LV) using only 8 switches. The TBMLI do not require diodes or capacitors for level generation, which reduces the complex modulation strategies used to handle capacitor balancing issues. Since the MLI uses transformer no special isolation is required.

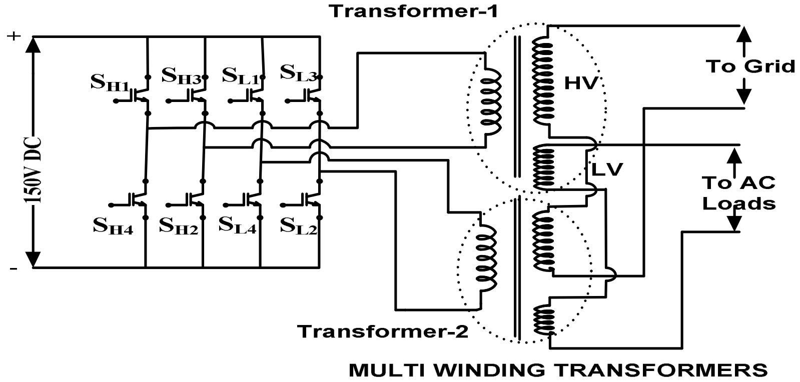


Fig.3. Proposed TBMLI

The proposed TBMLI generate 9 level phase voltage both at HV and LV ends. Two three winding transformers used in TBMLI has a primary and two secondary windings one for each LV and HV voltage levels. In the proposed topology number of voltage levels generated is highly depends on turns ratios of transformer. The turns ratio of transformer-1and 2 are 1: 3n and 1:n respectively to generate maximum voltage levels. In the proposed topology primary winding of transformers are excited from common DC source and secondary winding of transformers are connected in series. The equivalent circuit of three winding transformer is shown in fig.4 [19], [20]. Where $Z_1\lfloor\theta_1, Z_2\lfloor\theta_2$ & $Z_3\lfloor\theta_3$ are the equivalent impedances of the three winding respectively given by (1)-(3)

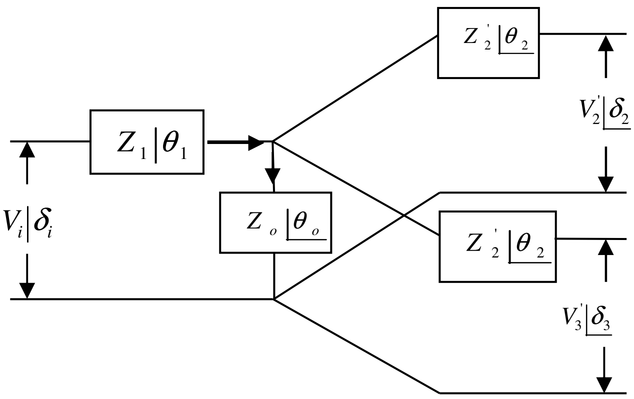


Fig.4. Equivalent circuit

$$Z_1 = Z_{1eq}^{c} - Z_{1eq}^{a} - Z_{1eq}^{b} \quad (1)$$

$$Z_2 = \frac{Z_{1eq}^{a} - Z_1}{K_1^2} \quad (2)$$

$$Z_3 = \frac{Z_{1eq}^{b} - Z_1}{K_2^2} \quad (3)$$

Where $Z_{1eq}^{a}\ Z_{1eq}^{b}$ *and* Z_{1eq}^{c} are the equivalent impedances obtained for different loss tests, K1 and K2 are the turn's ratio given by

$K_1 = \frac{N_1}{N_2}$ and $K_2 = \frac{N_1}{N_3}$ (4)

The switching stagey developed for the proposed TBLMI is illustrated in Table.I

Due to the ease of implementation, the well established multi-carrier PWM technique with 8 carrier signals as shown in fig.5. has been implemented[21],[22].

Table.1. Switching stagey for TBMLI

S.No	Level	Operating states of the switches							
		S_{H1}	S_{H2}	S_{H3}	S_{H4}	S_{L1}	S_{L2}	S_{L3}	S_{L4}
1	V	1	1	0	0	1	1	0	0
2	3/4V	1	1	0	0	1	0	1	0
3	1/2V	1	1	0	0	0	0	1	1
4	1/4V	1	0	1	0	1	1	0	0
5	0	1	0	1	0	1	0	1	0
6	-1/4V	0	1	0	1	0	0	1	1
7	-1/2V	0	0	1	1	1	1	0	0
8	-3/4V	0	0	1	1	0	1	0	1
9	-V	0	0	1	1	0	0	1	1

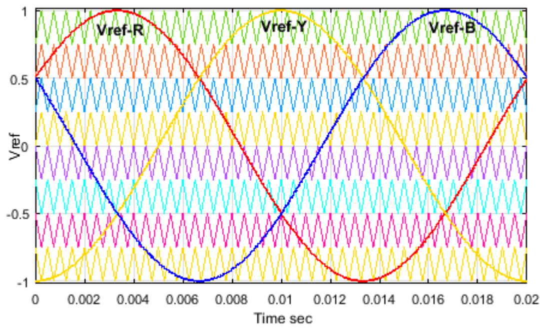


Fig.5. Multi-carrier PWM technique

2) Advantages of proposed TBMLI:

Besides generation of two different voltage levels, the other salient features of the proposed TBMLI include.

a) Reduced component count and associated issues

i. It eliminates the clamping diodes, capacitors and isolated sources that are employed in conventional MLI topologies this result in eliminating the issues related to voltage balancing in capacitors.

ii. As mentioned earlier the DC bus voltage is low compared to using of conventional MLI in the system resulting in employing low rated switches.

b) Scalability

i. This can be easily scalable to any voltage level (HV and LV)

ii. Further the levels can be increased from 9 to 21 by adding a coil and 4 switches

c) Low cost voltage booster

i. Due to reduced component count and low rated switches, the cost of the proposed TBMLI remains low compared to conventional MLI topologies

ii. The proposed topologies produces high voltage levels with low DC input voltage. Hence this can be used as a voltage booster.

III. PROPOSED δ - CONTROLLER

In any micro-grid optimal utilization of sources is of paramount importance and so is the power balancing. In this regard, an effective controller which serves the dual purpose is essential. This paper proposes a δ controller which serves the following objectives:

a) Effective Power balancing of the MG.
b) Maintain the state of health of battery.
c) Regulates DC and AC bus voltages.
d) Maintain stability of MG under different operating scenarios.

The block of the proposed δ controller is shown in fig.6. The proposed δ controller achieves the above mentioned objectives by changing the reference sine wave. The novelty of the controller lies in varying the reference sine wave both in magnitude and phase. It is well known fact that, the magnitude change varies the width of the inverter switching pulses there by regulating the AC bus voltages. The change in δ results in phase shift of the reference sine wave there by regulating the power flows in the system. Power balance eluviations of MG are given by (5)-(7).

$$P_{Grid} = \frac{V_1 V_3^{'}}{Z_3^{'}}\cos(\delta_3 - \delta_1 + \theta_3) - \frac{(I_1 Z_1)V_3^{'}}{Z_3^{'}}\cos(\delta_3 - \phi - \theta_1 + \theta_3) - \frac{V_3^{'2}}{Z_3^{'}}\cos(\theta_3) \quad (5)$$

$$P_{Grid} = P_{T/F\ Input} - (P_{2^{ed}\ Winding\_Input} + P_{primary\_Loss}) - P_{3^{ed}\ Winding\_Loss} \quad (6)$$

$$Q_{Grid} = \frac{V_i V_3^{'}}{Z_3^{'}}\sin(\delta_3 - \delta_1 + \theta_3) - \frac{(I_1 Z_1)V_3^{'}}{Z_3^{'}}\sin(\delta_3 - \phi - \theta_1 + \theta_3) - \frac{V_3^{'2}}{Z_3^{'}}\sin(\theta_3) \quad (7)$$

Where $Z_1\angle\theta_1, Z_2\angle\theta_2 \;\&\; Z_3\angle\theta_3$ are leakage impedances of thee windings respectively

Where $V_1\angle\delta_1, V_2^{'}\angle\delta_2 \;\&\; V_3^{'}\angle\delta_3$ are phase voltages of three windings respectively

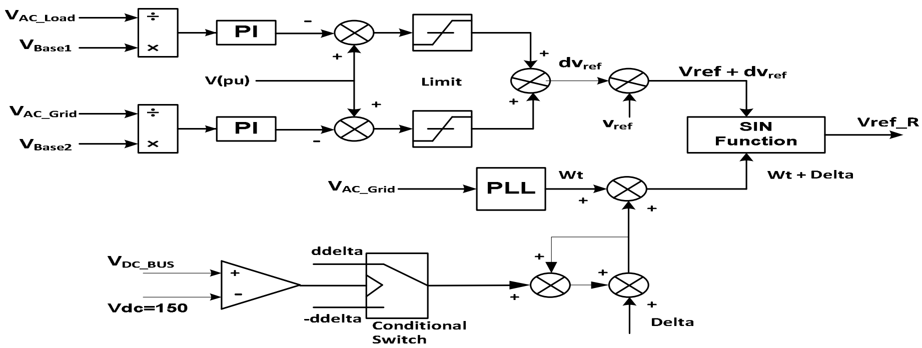


Fig.6. Proposed δ-Controller

The value of δ depends on the health of the battery, power generation and load demand. If the generation is exceeds the load demand the gets updated so as to charge the battery and pump reaming power to the grid. The charging of battery is given highest priority. If in case demand is more than generation, the δ modified in such way that power is pumped from the grid to meet the load demand but not to charge the battery. The detailed flow charts for different cases are illustrated in fig.7(a, b & c). Modulated reference signal generated to regulate or stabilize the MG are given by (10)-(12).

$$V_{ref_R} = (V_{ref} \pm \Delta V_{ref})\sin(wt \pm \delta) \quad (10)$$

$$V_{ref_Y} = (V_{ref} \pm \Delta V_{ref})\sin(wt \pm \delta - 120) \quad (11)$$

$$V_{ref_B} = (V_{ref} \pm \Delta V_{ref})\sin(wt \pm \delta + 120) \quad (12)$$

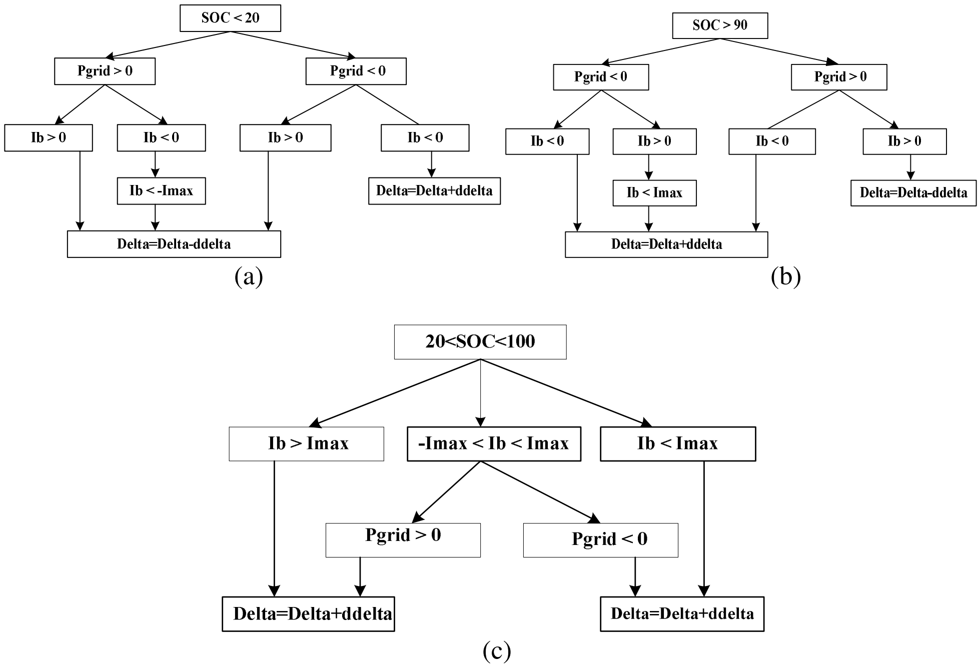


Fig.7. Power flows Algorithms for the MG system a) SOC < 20, b) SOC > 90, c) 20 < SOC < 90

IV. RESULTS AND ANALYSIS

In this paper a 25kW PV system, 25kW wind power capacity and C10, 1020Ah storage is considered to analyze the performance of δ controller for building based hybrid MG. The proposed microgrid consist of three buses DC bus (bus voltage V_{DC}=150V), LV AC bus (bus voltage V_{LVAC}=415V) and HV AC bus (bus voltage V_{HVAC}=11kV). These bus voltages are maintained constant irrespective of system parameter by δ -Controller and battery controller. In order verify proposed δ -Controller different case studies are carried out in simulation MATLAB/Simulink environment. Three case studies are performed to analyze dynamic behavior of the MG with small and gradual variation of demand and generation. To know the transient behavior of the proposed δ -Controller, three different fault case studies are performed on the MG.

1) Dynamic stability analysis of proposed system

Case-I (20<SOC<100): In this case battery is fully available for power balancing in the MG irrespective of generation and demand variation. Depending on the amount of generation and load the power angle δ is continuously updated to balance the power in the MG. The power flow in the MG is as shown in Fig.8. At t=4sec, total power generation (Pg) is 26kW (P_{wind}=15kW and P_{pv}=11kW) and total load demand (i.e. Pd=Pac+Pdc) at the same instant is 10kW. The difference of power is 16kW, charge the battery with maximum power of 15kW and remaining 1kW is delivered to grid. To verify the viability of the δ -Controller, the power has been increased from 10kW to 20kW at t=15 sec. At the same instant, the wind velocity is decreased thereby decreasing the generation of wind. The total generation is set in such a way that it equals to the demand. So at this instant no power is delivered or absorbed by battery and grid. Further at t= 16 sec, the generated power is further reduced to 11kW and demand to 15kW. The δ -Controller varies the value of delta so as to meet the demand through battery and grid remains ideal.

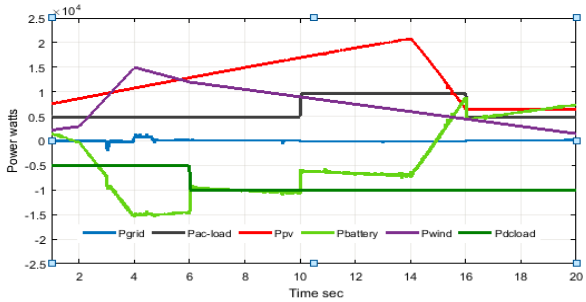


Fig.8. Power flows in MG for 20<SOC<90

Case-II (SOC > 90): As the battery is charged, the SOC will keep increasing. When the battery SOC is greater than 90%, the δ-Controller will stop charging the battery and send the surplus power to the grid. Whenever the demand increases, the energy stored in the battery will be released to compensate the demand by the δ -Controller. Power flow in the MG with battery SOC > 90 % is illustrated in fig.9. At t = 6sec, a DC load of Pdc=5kW is added to the DC bus (total DC load=10kW). The battery quickly responds to change in demand and latter on power delivered to the grid is smoothly decreased from 18kW to 13kW and battery power delivered is returned to study state by the δ-Controller. At t= 16sec, a AC load of Pac=5kW is switched off and the excess power due to loss of demand is quickly absorbed by the battery and then the δ gets updated to hand over power absorbed by the battery to grid.

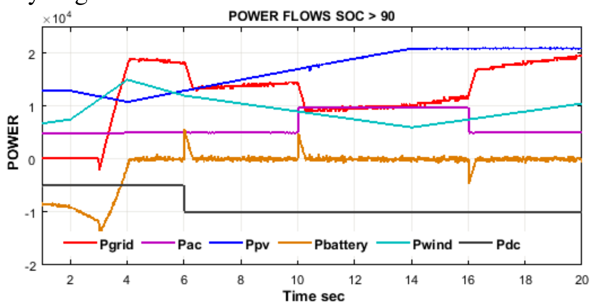


Fig.9. Power flows in MG for SOC > 90

Case-III (SOC < 20): In this case, the battery SOC is considered to be less than 20% which is the lower limit and hence the δ -controller stops releasing the power from battery for its protection. The PV array, wind and battery supplies power is supplying power to the DC and AC loads. At t= 2 sec, the battery SOC comes to the lower limit and power delivered by the battery slowly becomes zero. As power delivered by the battery comes to zero, in order to maintain power balance in the MG power delivered by the grid (P_{grid}) correspondingly increases. Total power generation (P_g=P_{wind}+P_{pv}) is greater than total demand (P_d=P_{ac}+P_{dc}) for time t=3.7 sec to 7.9 sec. This excess power charge the battery as shown in fig.10. P_g is less than P_d for t > 8sec, δ -controller diverts the excess power to charge the battery. At t= 8 sec, P_g<P_d and stored energy in the battery will fill the gap between demand and generation (i.e. $P_{battery}$=8kW, P_g=7kW and P_d=15kW).

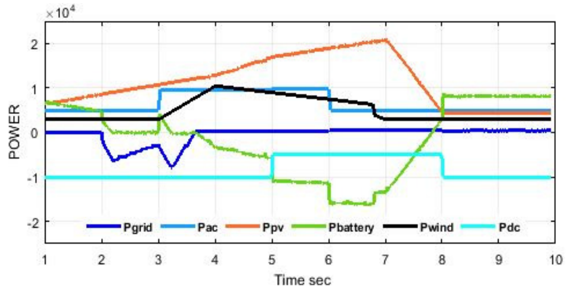
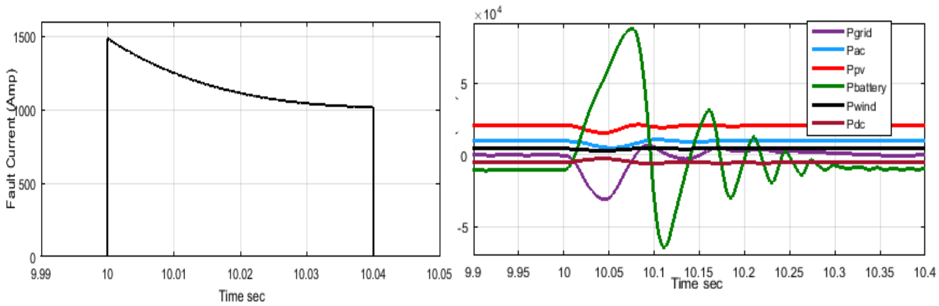


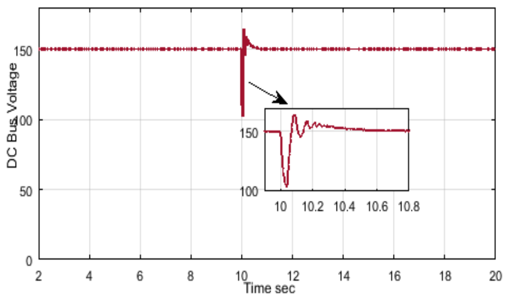
Fig.10. Power flows in MG for 20>SOC

2) Transient stability analysis of proposed system

Case-1(DC bus fault): At t= 10sec, 2cycles DC bus fault is considered with high fault current as shown in Fig.11(a) and fault resistance of 0.1 ohm. In the MG battery is having low inertia, so it is more sensitive to parameter variation. In the Fig.11 (b) an under damped power oscillations are produced in battery power and grid power. Battery power exhibit more power oscillation than other sources and it takes 0.3 sec to stabilize. The δ -controller acts immediately after the fault and stabilize the DC bus voltage within a less time as depicted in Fig.11(c).



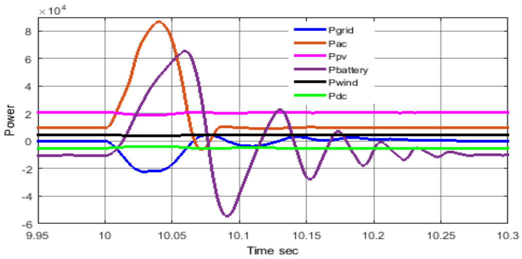
a b



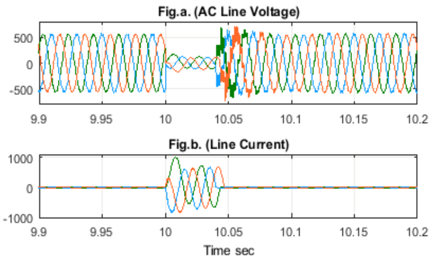
c

Fig.11. a) DC Fault current, b) Power oscillations in MG, c) DC bus voltage

Case-2(Fault on AC load bus): A 2 cycles three phase short circuit fault occurred on LV AC bus at time t= 10 sec with fault resistance of 0.1 ohms. As soon as the fault occurs, the δ -Controller varies the value of δ so as to stabilize the system. The LV bus power stabilizes within 0.07 sec. However, due to low time constant of the battery, it takes 0.25 sec to stabilize. The power flow dynamics of MG is shown in Fig.12(a). The LV bus voltage current profile is depicted in Fig.12(b). It can be observed that, due three phase short circuit fault on LV bus, bus voltage is interrupted for 2 cycles and it is settle down within 0.06 sec. The DC bus voltage undergoes an under damped oscillations due to the fault on LV AC bus. The δ -Controller supports to battery controller and stabilizes the DC bus voltage with in the 0.4 sec as shown in Fig.12(c).



(a)



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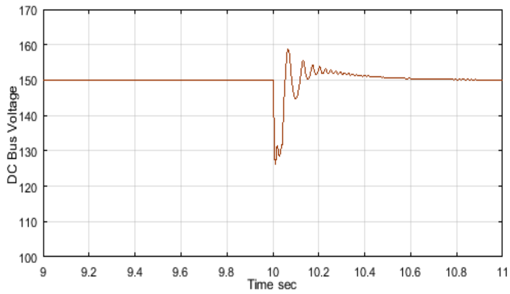
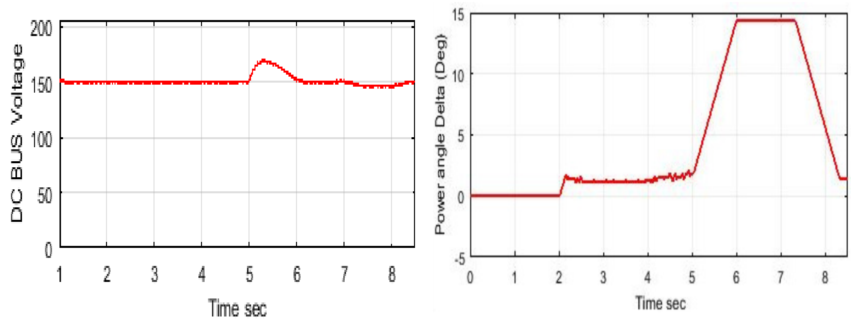


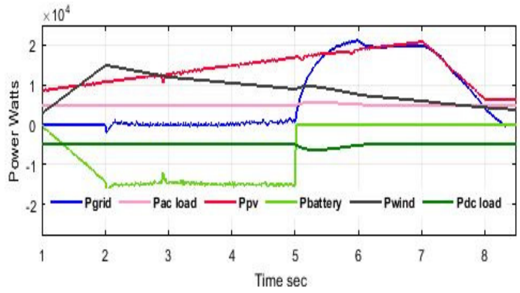
(c)

Fig.12. a) Power flows in the MG, b) 400V AC bus voltage and fault current, c) DC bus voltage

Case-3 (Battery converter fault): The battery converter open circuit fault on a switch, while the battery is charging with maximum capacity (i.e. $P_{battery}$=15kW) is considered. The main objective of battery charge controller is maintain DC bus voltage constant irrespective of generation and demand variations and the voltage profile of DC bus. To check the viability of proposed controller under this condition, the switch is open circuited at t=5sec when the battery is charging at maximum capacity as mentioned earlier. Generally, this scenario results in high voltage rise in DC bus voltage due to MPPT controllers. However, the proposed controller limits this rise to 12% as depicted in fig.13(a). Power angle variation and power flows with loss of battery load and with variation of generation and demand are shown in fig.13(b). and fig.13(c). respectively. Just before the fault, total power generation=26kW, total demand=10kW, battery charging power=15kW and power delivered to grid=1kW. After fault battery power demand is lost and it makes power imbalance in the MG. Delta controller updates the power angle delta (i.e. 2.5^o to 15^o) to bring back the power balance in the MG.



(a) (b)

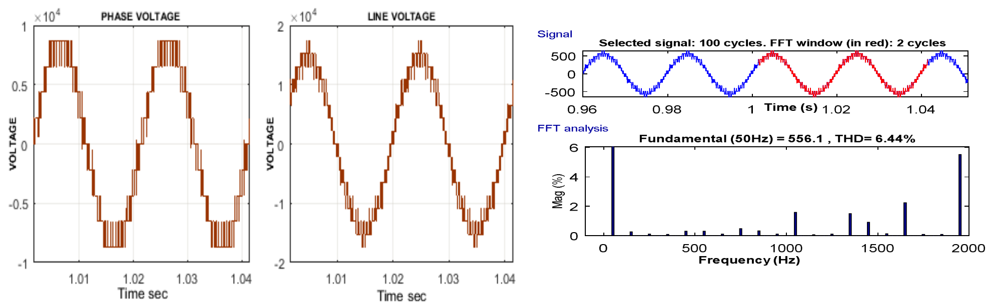


(c)

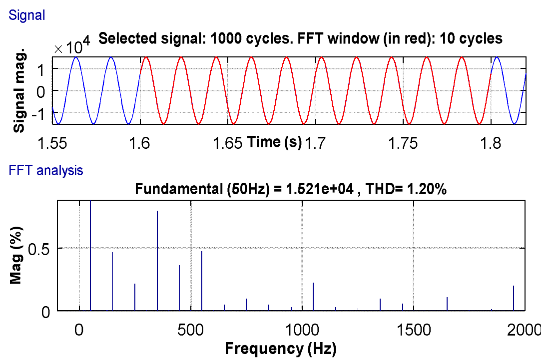
Fig.13. a) DC bus voltage, b) Power angle delta profile, c) Power flows in the MG

3) Proposed MLI

The proposed transformer based MLI excited from 150V DC bus generates 9 levels (17 levels in line to line) in LV and HV phases. Simulation results of Phase voltage and line voltage of proposed TBMLI are depicted in fig.14 (a). As observed from Fig. 14 (b) and 14 (c) the THD of the voltage with and without filters are 6.44% and 1.2% respectively.



(a) (b)



(c)

Fig.14. : (a) Phase voltage and line voltage of TBMLI, (b) THD of 400 AC Voltage without filter (c) THD of 11kV AC voltage with filter.

V. CONCLUSIONS

In this paper a building based MG structure with solar and wind as main sources and battery as auxiliary source has been proposed. A conventional inverter/MLI has been replaced by TLBMLI to reduce the component count and issues related to voltage balancing and stress in MLI's. The proposed unified delta controller was observed to satisfy the following objectives.

i. Efficient power management in MG system.
ii. Effective battery management to maintain state of charge of the battery.
iii. Improved MG system stability.
iv. Regulated voltage across DC and AC buses with and without battery

Further, exhaustive investigations carried out validated the effectiveness of the proposed MG system and delta controller for a 50 kW (25 kW solar, 25 kW wind and 1020 Ah battery) MG system under various operating scenarios considering both source and load intermittencies.

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Reference

[1] M. H. Nehrir *et al.*, "A Review of Hybrid Renewable / Alternative Energy Systems for Electric Power Generation :," *IEEE Trans. Sustain. Energy*, vol. 2, no. 4, pp. 392–403, 2011, doi: 10.1109/TSTE.2011.2157540.
[2] V. Prema and U. R. K, "Integrated Intelligent Power Management Strategy (IIPMS) to optimize green energy usage in standalone microgrid," *2018 20th Natl. Power Syst. Conf.*, pp. 1–6, 2018.
[3] X. Zhang, T. Zhao, W. Mao, D. Tan, and L. Chang, "Multilevel Inverters for Grid-Connected Photovoltaic Applications: Examining Emerging Trends," *IEEE Power Electron. Mag.*, vol. 5, no. December, pp. 32–41, 2018, doi: 10.1109/MPEL.2018.2874509.
[4] F. Nejabatkhah; and Y. W. Li, "Overview of Power Management Strategies of Hybrid AC/DC Microgrid," *IEEE Trans. Power Electron.*, vol. 30, no. 12, pp. 7072–7089, 2015, doi: 10.1109/TPEL.2014.2384999.
[5] H. Kanchev, D. Lu, F. Colas, V. Lazarov, B. Francois, and S. Member, "Energy Management and Operational Planning of a Microgrid With a PV-Based Active Generator for Smart Grid Applications," *IEEE Trans. Ind. Electron.*, vol. 58, no. 10, pp. 4583–4592, 2011, doi: 10.1109/TIE.2011.2119451.
[6] A. Merabet, K. T. Ahmed, H. Ibrahim, R. Beguenane, and A. M. Y. M. Ghias, "Energy Management and Control System for Laboratory Scale Microgrid Based Wind-PV-Battery," *IEEE Trans. Sustain. Energy*,

vol. 8, no. 1, pp. 145–154, 2017, doi: 10.1109/TSTE.2016.2587828.

[7] B. S. Borowy; and Z. M. Salameh, "Methodology for Optimally Sizing the Combination of a Battery Bank and PV Array in a Wind/PV Hybrid System," *IEEE Trans. Energy Convers.*, vol. 11, no. 2, pp. 367–375, 1996.

[8] Z. Yi, S. Member, W. Dong, and A. H. Etemadi, "A Unified Control and Power Management Scheme for PV-Battery-Based Hybrid Microgrids for Both Grid-Connected and Islanded Modes," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 5975–5985, 2018, doi: 10.1109/TSG.2017.2700332.

[9] P. Siano, C. Cecati, H. Yu, S. Member, and J. Kolbusz, "Real Time Operation of Smart Grids via FCN Networks and Optimal Power Flow," *IEEE Trans. Ind. Informatics*, vol. 8, no. 4, pp. 944–952, 2012, doi: 10.1109/TII.2012.2205391.

[10] S. Peyghami, S. Member, H. Mokhtari, and S. Member, "Autonomous Operation of a Hybrid AC / DC Microgrid With Multiple Interlinking Converters," *IEEE Trans. Smart Grid*, vol. 9, no. 6, pp. 6480–6488, 2018, doi: 10.1109/TSG.2017.2713941.

[11] B. R. Naidu, G. Panda, and P. Siano, "A Self-Reliant DC Microgrid : Sizing , Control , Adaptive Dynamic Power Management , and Experimental Analysis," *IEEE Trans. Ind. Informatics*, vol. 14, no. 8, pp. 3300–3313, 2018, doi: 10.1109/TII.2017.2780193.

[12] P. Lin, S. Member, P. Wang, C. Jin, and J. Xiao, "A Distributed Power Management Strategy for Multi-Paralleled Bidirectional Interlinking Converters in Hybrid AC / DC Microgrids," *IEEE Trans. Smart Grid*, vol. 10, no. 5, pp. 5696–5711, 2019, doi: 10.1109/TSG.2018.2890420.

[13] R. C. Dugan;, M. F. McGranaghan;, S. Santoso;, and H. W. Beaty, *Electrical Power Systems Quality , Second Edition*, Second. Mc Graw-Hill, 2004.

[14] D. Somayajula, S. Member, M. L. Crow, and A. P. Stage, "An Ultracapacitor Integrated Power Conditioner for Intermittency Smoothing and Improving Power Quality of Distribution Grid," *IEEE Trans. Sustain. Energy*, vol. 5, no. 4, pp. 1145–1155, 2014, doi: 10.1109/TSTE.2014.2334622.

[15] S. Anwar, A. Elrayyah, Y. Sozer, and S. Member, "Efficient Single-Phase Harmonics Elimination Method for Microgrid Operations," *IEEE Trans. Ind. Appl.*, vol. 51, no. 4, pp. 3394–3403, 2015, doi: 10.1109/TIA.2014.2387472.

[16] P. F. Ribeiro *et al.*, "Energy Storage Systems for Advanced Power Applications," *Proc. IEEE*, vol. 89, no. 12, pp. 1744–1756, 2001, doi: 10.1109/5.975900.

[17] D. Somayajula, M. L. Crow, and A. P. Stage, "An Integrated Dynamic Voltage Restorer-Ultracapacitor Design for Improving Power Quality of the Distribution Grid," *IEEE Trans. Sustain. Energy*, vol. 6, no. 2, pp. 616–624, 2015, doi: 10.1109/TSTE.2015.2402221.

[18] Y. V. P. Kumar and B. Ravikumar, "A simple modular multilevel inverter topology for the power quality improvement in renewable energy based green building microgrids," *Electr. Power Syst. Res.*, vol. 140, pp. 147–161, 2016, doi: 10.1016/j.epsr.2016.06.027.

[19] V. M. Suslov and V. A. Bosneaga, "Method of Parameters Determination for Multi-Winding Transformer Equivalent Circuit in the Form of Multi-Beam Star," *Proc. 2019 8th Int. Conf. Mod. Power Syst. MPS 2019*, pp. 1–4, 2019, doi: 10.1109/MPS.2019.8759746.

[20] J. A. Martinez-Velasco, "Equivalent circuit of transformers with control of voltage and phase angle," *Electr. Power Syst. Res.*, vol. 81, no. 7, pp. 1349–1356, 2011, doi: 10.1016/j.epsr.2011.01.019.

[21] S. Thamizharasan, J. Baskaran, S. Ramkumar, and S. Mubarak Ali, "Modified carrier PWM strategies for multilevel inverters," *EEE Trans. Ind. Electron.*, vol. 49, no. 4, pp. 51–54, 2013, doi: 10.1109/ICCPEIC.2013.6778497.

[22] P. Hemachandu and V. C. V. Reddy, "A Critical Evaluation of Advanced Multi-Carrier Modulation Scheme for 15-Level Inverter via PSO-PID Controller," *Procedia Technol.*, vol. 23, pp. 240–247, 2016, doi: 10.1016/j.protcy.2016.03.023.