A Review on an Islanded Microgrid Considering Demand side Management Capability

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I ABSTRACT:AnewVoltageunbalancemitigationschemeforanislandedmicrogridbycoordinatingphotovoltaic(PV)grid-tied inverters, and thermostatically controlled loads (TCLs). A negative sequence compensation loop working in parallel with a positive sequence compensation loop is designed for PV inverters for VU mitigation.Inverter-based distributed generators (DGs) have been customarily used for voltage unbalance (VU) mitigation in microgrids.The sole dependency on DGs for VU mitigation may not be justified, particularly in islanded microgrids. Demand side management (DSM) can be a potential candidate for VU mitigation in microgrids. Also, a voltage dependent model of TCLs, unlike the conventional one, along with the control strategy for VU mitigation is presented. The proposed control of TCLs not only minimizes VU, and hence increases the dynamic reactive power reserve of the inverter based DGs, but also effectively maintains the customers' thermal comfort. The proposed VU mitigation scheme is studied with comprehensive simulations in PSCAD/EMTDC, and is verified using a real-time digital simulator.

Index Terms—Voltage unbalance compensation, islanded microgrid, positive and negative sequence controller, thermostatically controlled loads, real-time simulation.

II. INTRODUCTION

MICROGRIDS have been envisaged as efficient entities for the deregulation of conventional power systems, and hence expanding the penetration of renewable energy system (RES) in power generation portfolios.
However, issues regarding reliability, power quality, and power system security have been posing challenges in microgrids, especially in the islanded mode of operation, with high penetration of RES. With an increase in inverter-interfaced DG units and nonlinear loads in microgrids, the power quality issue has become a crucial one . Voltage unbalance is one of the important constituent of the power quality issues.
The major source of VU is the uneven distribution of singlephase loads that are connected either between one phase and the neutral or between two phases. Moreover, VU can also occur as a result of asymmetrical line and transformer impedances, asymmetrical line faults, open wye and delta transformer banks, and non-linear loads [3]. During a VU , power systems incur increased loss and become susceptible to instability. Induction motors, power electronic converters, and adjustable speed drives (ASDs) are impacted by VU. Particularly, induction motors and ASDs suffer from de-rating, mechanical stress, overheating, and decrement in lifetime. In power electronic converters, VU causes double frequency power oscillations resulting in ripples in dc-link voltage, and an increase in reactive power production. The International Electrotechnical Commission (IEC) recommends the maximum limit of 2% of voltage unbalance factor (VUF) in electrical supply system [3]. Also, the International Council on Large Electric Systems (CIGRE) Working Group 36.07 suggests a maximum of 2% VUF for medium voltage (MV) power systems . The same standard of VU mitigation has been used in this paper. The ideal solution to mitigate VU is to distribute loads equally among phases. A network reconfiguration algorithm which switches time variant loads among phases either manually or using automatic feeder switching has been presented in. The target of the reconfiguration was to minimize distribution system losses which inherently contributed to the balancing of loads among phases. An optimization study for rearranging and balancing phases in the primary side of the distribution transformer has been presented in .
In the residential loads are dynamically switched among phases to reduce the VU in low voltage networks employing static transfer switches, a central controller, and end-use controllers. the control strategy in this paper does not transfer loads from one phase to the other but rather the phase voltages are balanced by switching the TCLs connected to their respective phase. Many recent studies have used electric vehicles (EVs) as a DSM entity for VU mitigation . Recently, a concept of an electric spring (ES) which is connected between non-critical loads such as TCLs and system bus has been widely studied as a fast demand response. Such an ES has been primarily studied for three phase voltage regulation , harmonic supression of critical loads[10],and mitigation of power fluctuations. However, the sole dependency on demand-side might not be always sufficient for VU mitigation as DSM is directly linked to the customers' quality of service (QoS). Besides the demand-side, DG units and flexible alternating current transmission system (FACTS) devices have been used for VU mitigation. Series and shunt active power filters have been used to mitigate the VU . The series active power filters compensated the grid's negative sequence voltage by injecting negative sequence voltage in series with the grid. Shunt active power filters mitigated the VU by balancing the line currents through an addition of reactive elements in parallel to the loads. Microgrids having inverter interfaced DG units have a potential to mitigate

VU by deploying these DG units rather than the dedicated FACTS devices. Several studies have deployed inverter-interfaced DG units for mitigating VU in microgrids. A hierarchical control of the inverter-based DG units for VU mitigation in islanded micorgrids, which shares the negative sequence current among the DG units, has been presented in. Also, a virtual negative sequence impedance controller for DG units of a multi-bus medium voltage (MV) islanded microgrid has been employed to mitigate VU in . Further, the BESS inverter has been utilized to mitigate VU in both islanded and grid-tied mode of microgrid operation in . Authors in [19] have proposed two strategies for grid VU compensation: the first strategy dedicated to reduce the effect of VU in DG units such as power oscillation, and dc link voltage variation, and the second one focused on the minimization of VU by injecting negative sequence current from DG units in phase with grid's negative sequence current. A VU mitigation technique which dynamically shares reactive current among distributed PV inverters connected at the transmission level has been presented. Converters control of the doubly-fed induction generator has been deployed to mitigate VU. However, the methods are exclusively dependent on the generation-side for VU mitigation. In microgrids, especially in islanded microgrids, such an over-dependency on the DG units for VU mitigation may not always be justified as these DG units should be stringent on providing grid ancillary service such as frequency and voltage regulations. Moreover, VU mitigation during saturation of these DG units should also be taken into consideration. Therefore, the coordination between the generation-side and the demand-side for VU mitigation is justifiable. The studies performed in have deployed the coordination between electric vehicles (EVs) and PV to mitigate the voltage unbalance in the grid. The coordination is based on the charging pattern of EVs and PV power generation. However, this paper deploys residential TCLs as DSM entities coordinated with PV inverters for VU mitigation. TCLs such as heating, ventilation, and air-conditioning loads (HVACs) and electric water heaters have been widely used as components of DSM for grid ancillary services in microgrids. In literature, the use of TCLs in voltage regulation and VU mitigation has not been widely studied as done for frequency regulation. Some recent studies have presented the concept of manipulation of TCLs in voltage regulation. Since TCLs such as HVACs, heat pumps, and refrigerators are driven by induction motors, they also consume some reactive power in addition to the active power. However, the reactive power capability of TCLs has been ignored in the literature. Therefore, this paper firstly modifies the conventional model of TCLs to consider the reactive power consumption and coordinates the TCLs with the PV inverter for VU mitigation. Moreover, the customers' thermal comfort has been deliberately maintained during the manipulation of TCLs for VU mitigation.

III. SYSTEM DESCRIPTION

The layout of an islanded microgrid under study is shown in Fig. 1. The microgrid is developed in PSCAD/EMTDC. The test microgrid has 1 MVA diesel generator (DZ), 1.3 MVA PV power system, and 1.5 MWh BESS on the generation side.

The PV power system and the BESS are connected to 11 Kv point of common coupling (PCC) through DC/AC inverters, step-up transformers, and cables.

A 0.15 MVA induction motor, and unbalanced loads at L1 and L2 bus constitute the demand-side. At the L1 bus, three phases are unevenly loaded to create VU in the microgrid.

In addition to the single-phase loads, line to line loads are also the source of VU . Therefore, line to line loads between phase A and B are also considered. Around 25% of the loads in each phase of the L1 bus are considered as distributed TCLs. The TCLs are mathematically modeled in MATLAB and are interfaced with the other microgrid components implemented in PSCAD/EMTDC during the simulation.

The L1 bus is connected to PCC through Y/Δ step-up transformer and cable. The L2 bus connected at 11 Kv PCC has single-phase loads in phase A, and line to line loads between phase A and B. Phase C is left open to create further voltage unbalance in the microgrid.

In the studied microgrid, 1 MVA base is considered for the conversion of system parameters into per unit (pu).

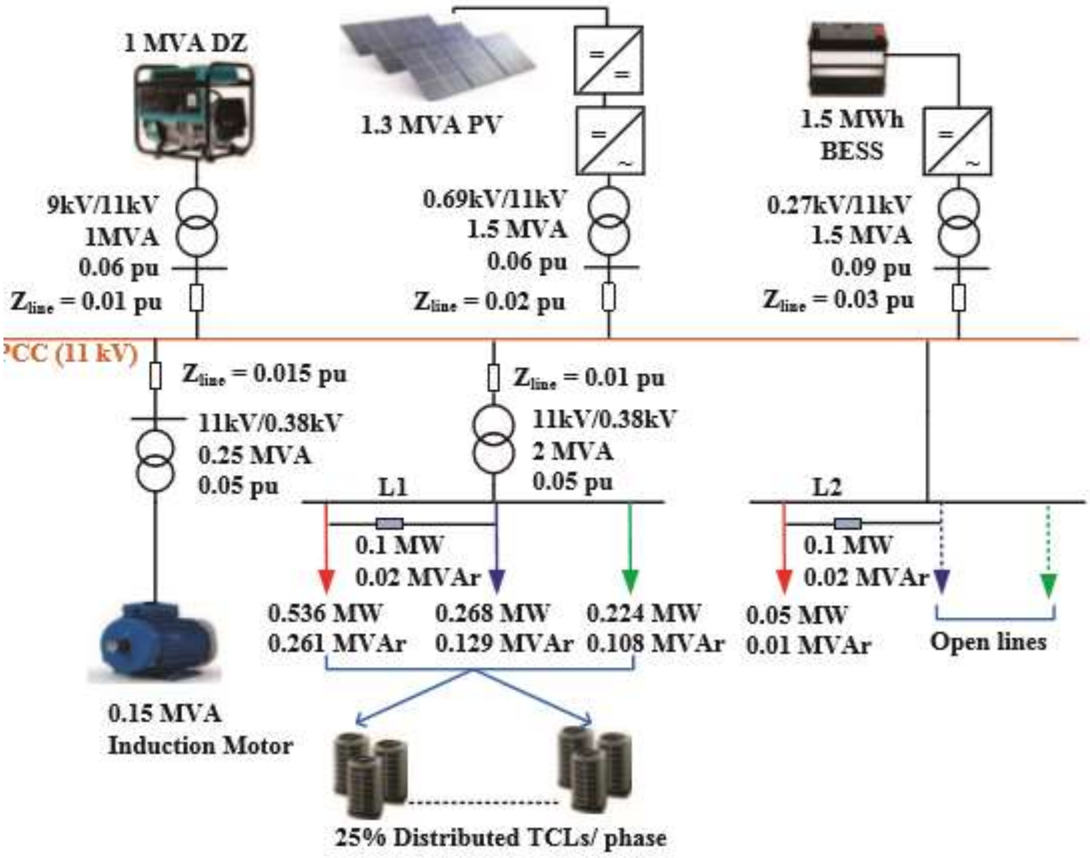


Fig. 1. Configuration of an islanded microgrid under study.

IV. PV POWER SYSTEM CONTROL

An unbalanced operation of PV inverter requires additional control schemes.

The schemes can be a modified positive sequence control loop or a negative sequence control loop operating in parallel with the positive sequence control loop. This study controls the PV inverter based on positive and negative sequence control loops. In both afore mentioned schemes, the extraction of positive and negative sequence components of AC voltages and currents is essential.

A. Positive and Negative Sequence Extraction

The positive and negative sequence components are extracted using the method presented .

During the unbalanced operation of power systems, AC voltages and currents compose positive and negative sequence components

where F is a general representation of the instantaneous value of three-phase AC voltage or current. The integer n denotes the phase quantities of F, i.e. $n \in (0,1,2)$. Variables ω and φ stand for synchronous speed and phase angle shift of F respectively. The vector representation of these quantities expressed in the synchronous reference frame is depicted in Fig. 2.

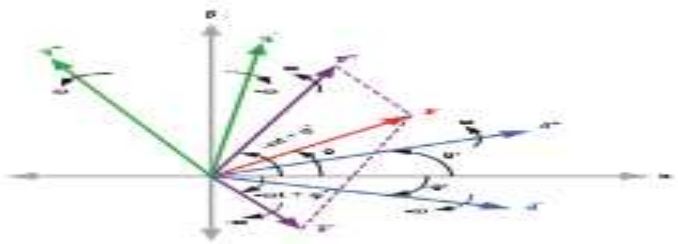


Fig. 2. Vector representation of AC voltage and current in synchronous reference frame.

The negative and positive sequence components of three-phase quantities decomposed into the stationary αβ reference frame The quantities expressed in the αβ reference frame can be transformed to a synchronously rotating reference frame, dq, using the synchronous speed of F. By expressing the threephase AC voltage and current in the dq frame, these AC voltages and currents are converted to DC terms. Moreover, the decoupled d and q axes allow separate control of the active and reactive powers. The AC voltage in the dq frame can be expressed as

where θ= ωt is the synchronizing phase angle which is determined using phase locked loop in this study. The extracted dq sequence components are usually passed through notch filters (NF) or low pass filters to avoid the noise from transformation.

B. Proposed Control Strategy of PV for Voltage Unbalance Mitigation

Fig. 3 depicts a flowchart for PV inverter control strategy designed for balanced and unbalanced operation of the microgrid. The control strategy is basically divided into two blocks: (i) Measurement & Calculation, and (ii) Control. In the first block, instantaneous values of three-phase AC voltage and current, and root mean square (rms) value of the voltage at the terminal of the PV power system are measured. The measured rms voltage is compared with the reference voltage (Vref = 1pu), and hence the voltage deviation (ΔV) is calculated. The sequence components of the PCC voltage and current are extracted. Then, the VUF is calculated using the following equation:

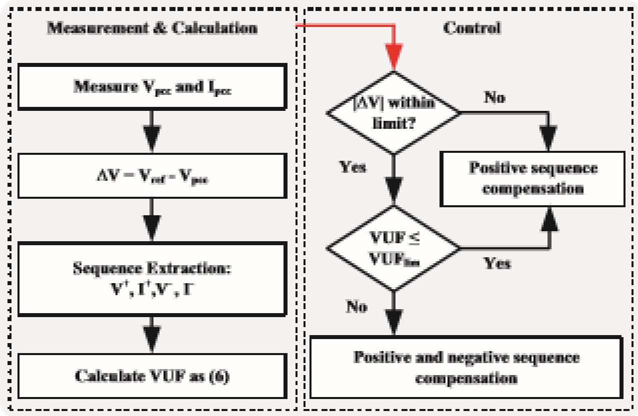


Fig. 3. PV power system control strategy.

In the Control block,|ΔV|is checked against its lower limit (0.95 pu) and upper limit (1.05 pu). On violating the limits for |ΔV|, the PV inverter is controlled for regulating the PCC voltage to Vref through the positive sequence compensation. Having PCC voltage regulated, VUF is checked against its acceptable limit (V UFlim = 2%) after which the PV inverter provides the negative sequence compensation along with the positive sequence compensation.

.C. Positive and Negative Sequence Controller of PV Inverter

The control diagram for the sequence controllers implemented in the PV inverter is shown in Fig. 5. After extraction, the sequence components are sent to their respective sequence controllers. The positive sequence controller is dedicated for controlling the dc link voltage and grid voltage during balanced and unbalanced operation of the PV inverter. The negative sequence controller mitigates the grid's VU by compensating negative sequence voltages of the grid. Both sequence controllers have the d and q axes controllers. Moreover, the sequence controllers have similar architecture of the outer voltage control loop and the inner current control loop. However, there exists a major difference in adjusting the reference output currents of the outer voltage control loop. The adjustment of the current limiter among sequence controllers has been introduced in and explained further. The vectorial representation of the positive (I+) and negative (I+) sequence currents during the unbalanced operation is depicted in Fig. 4

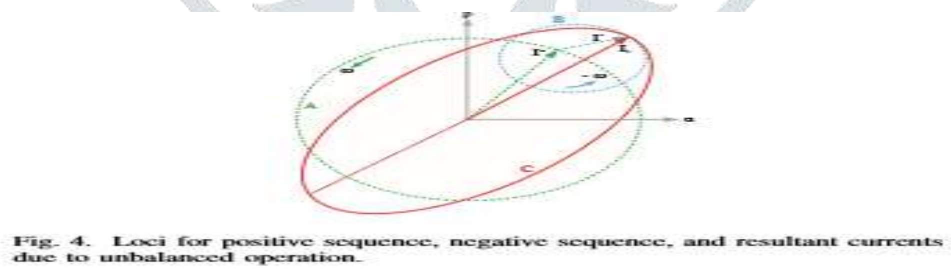


Fig. 4. Loci for positive sequence, negative sequence, and resultant currents due to unbalanced operation.

In Fig. 4, the positive sequence current is encompassed by circle A which rotates at synchronous speed (ω). During balanced conditions, circle A is the only locus of inverter current. The negative sequence current follows the locus of circle B which rotates at speed −ω. Eclipse C is the locus of net current which comes from the vector summation of positive and negative sequence currents. The double frequency component in the net current of the inverter is due to the negative sequence current. The inverter current in becomes maximum . The net current of the inverter also includes the overloading capacity on top of its rated capacity. As stated in Section III-B, voltage regulation is prioritized against VUF mitigation. Therefore, the limit for the positive sequence current is equal to the maximum current limit of the inverter, i.e. I+ ref = It. Within the positive sequence controller, dc link voltage regulation is emphasized against grid voltage regulation. Hence, the q+ axis current limit is adjusted dynamically.

The negative sequence compensation from PV inverter is available only if the positive sequence current is less than the maximum inverter current. Therefore, the negative sequence controller current is adjusted dynamically After allocating sequence currents, the inner current control loop of the sequence controllers determine their respective reference voltage in dq axes. Finally, these reference are summed up and sent to control the voltage source converter.

V. THERMOSTATICALLY CONTROLLED LOADS

TCLs such as HVAC can be viewed as a potential candidate of DSM for voltage unbalance mitigation in microgrids. The flexibility of TCLs operation within a specified dead band of temperature and reactive power consumption of TCLs rationalizes their use in voltage unbalance mitigation. TCLs' manipulation must consider their internal dynamics of temperature, physical restrictions in their operating states (ON/OFF), and their nature of distribution.

A. Modeling of Thermostatically Controlled Loads

The conventional modeling approach of TCLs does not account for the voltage dependency on active power consumption of TCLs. Moreover, reactive power consumption of TCLs has been ignored. This study considers the aforementioned issues in TCLs modeling. Considering the voltage dependency of active power, the TCL dynamic equation, expressed in hybrid state discrete time model.

Fig. 5. Positive and negative sequence controller implemented on PV inverter.

In this study, the values of coefficients of Z, I, and P for air-conditioners are taken from and presented in Table I in the Appendix. The remaining parameters used for the TCLs modeling are presented in Table II in the Appendix.

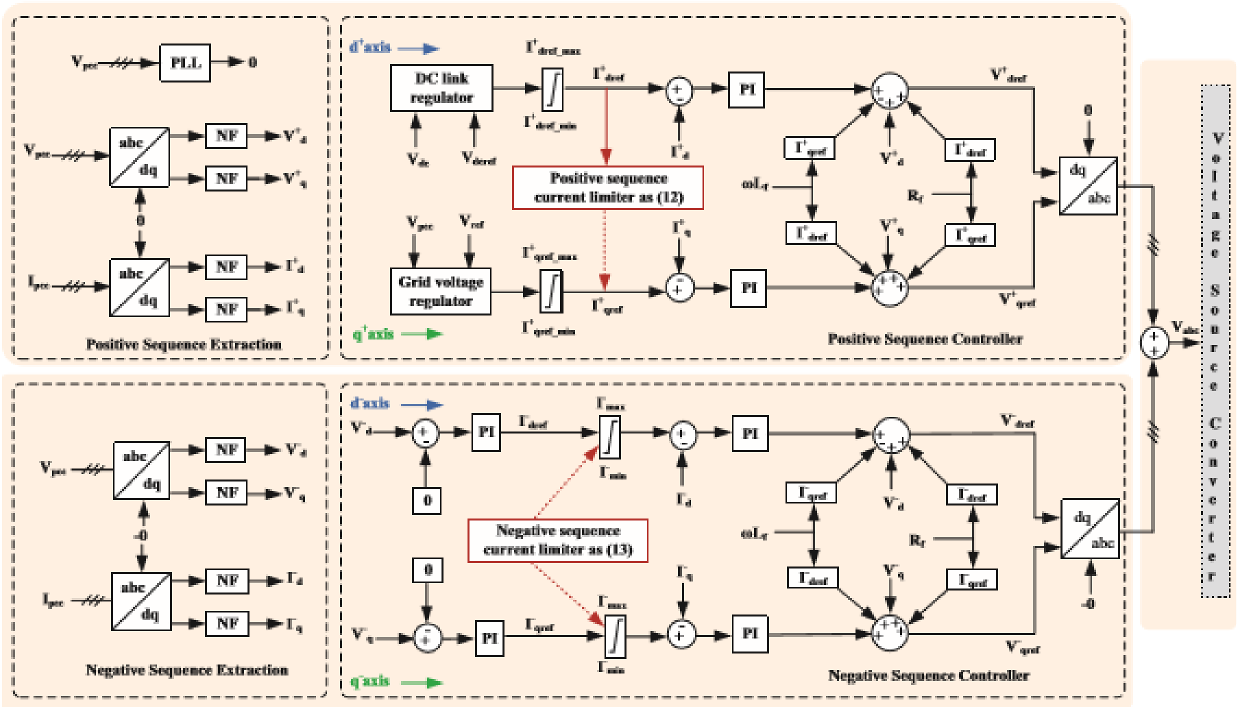


Fig.5. positive and negative sequence controller implemented on PV Inverter

B. Control Strategy of TCLs for VUF Mitigation

Fig. 6 depicts the proposed control structure of cooling TCLs for VUF mitigation. It is basically divided into three sections: (i) Aggregation; (ii) Temperature Control; and (iii) TCL control. The proposed strategy is developed in a way that TCLs' manipulation is prioritized for frequency regulation against VUF mitigation. Most importantly, the control strategy respects customers' thermal comfort even during the manipulation of TCLs for frequency and VUF regulation.

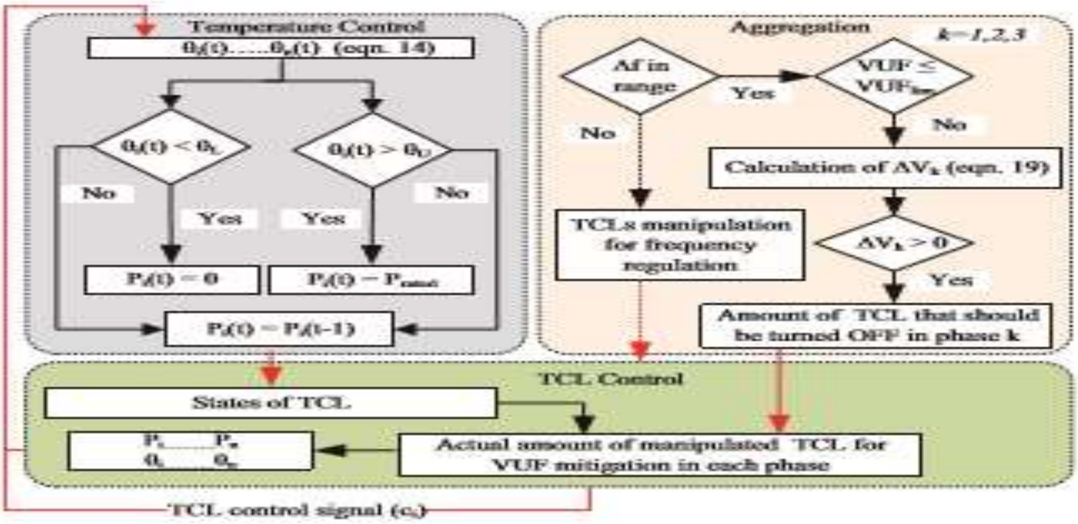


Fig. 6. Proposed TCL operation and control for VUF mitigation

SIMULATION RESULTS

In this study, the proposed control scheme is implemented to maintain the VUF below 2% using PV inverter and TCLs. In order to show the effectiveness of the proposed scheme, there are four major tests examined in this work: (i) Capability of TCLs to mitigate VUF; (ii) Capability of PV inverter to mitigate VUF; (iii) Coordination between PV inverter and TCLs for VUF mitigation; and (iv) Effect of TCLs' manipulation on frequency. The tests are conducted in an islanded microgrid developed in PSCAD/EMTDC. The time-domain simulation results are analyzed in the following subsections.

A. Capability of TCLs to Mitigate VUF

In order to verify the capability of TCLs to participate in VU mitigation, a highly unbalanced load profile at the L1 bus (see Fig. 1) is simulated. The loads at L2 bus is not connected for this scenario. The negative sequence controller of the PV inverter is deactivated for this simulation case. As shown in Fig. 7,

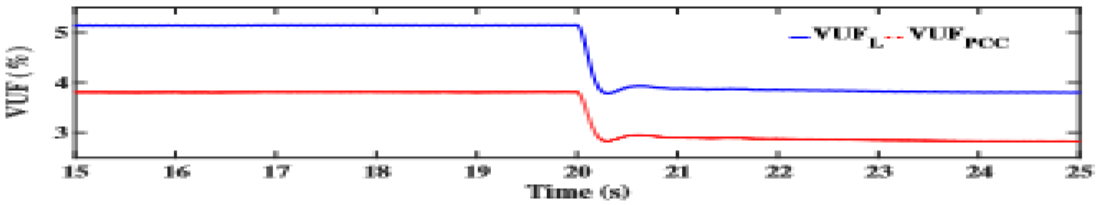


Fig.7. voltage unbalance factor measured at PCC and load bus.

The VUF measured at the load bus and at the PCC, prior to the application of TCLs' manipulation, are 5.1% and 3.1% respectively. This difference of VUF is due to the connection of loads to PCC through Y/Δ transformer. TCLs are manipulated at 20 s. As a result, the VUF decreased as shown in Fig. 8. The decrease in VUF can also be verified from Fig. 8 where the difference between rms values of phase voltages decreased after 20 s. The rms voltage of phase B

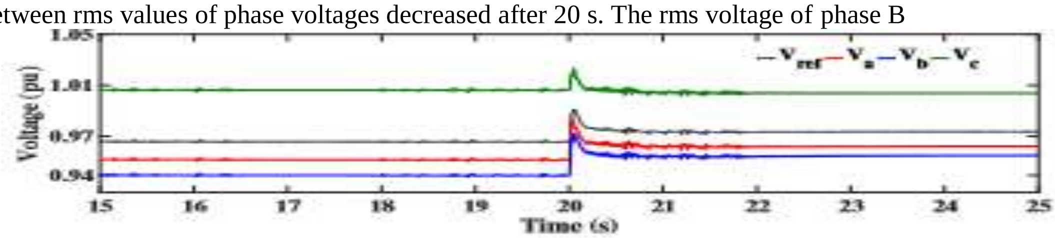


Fig. 8. Phase Voltages of the unbalanced load bus.

before 20 s is intentionally made below 0.9 pu (below voltage regulation lower limit = 0.9 pu) to show the benefit of this strategy even for the regulation of the under voltage. The manipulation of TCLs is done according to the deviation of phase voltages from the reference voltage (see equation 20). Since the study uses one-dimensional manipulation of TCLs (i.e. only turns OFF the ON state TCLs but does not turn ON the OFF state TCLs), TCLs connected to those phases with positive ΔV (see equation 19) are only manipulated. In Fig. 9, as expected, the TCLs of phase A and B are manipulated while TCLs connected to phase are not manipulated. A small decrease in the active and reactive power consumption of TCLs of phase C after 20 s is because of the voltage dependent model of TCLs. Although the manipulation of TCLs could not mitigate the VUF below 2%, the capability of TCLs for VUF mitigation is established.

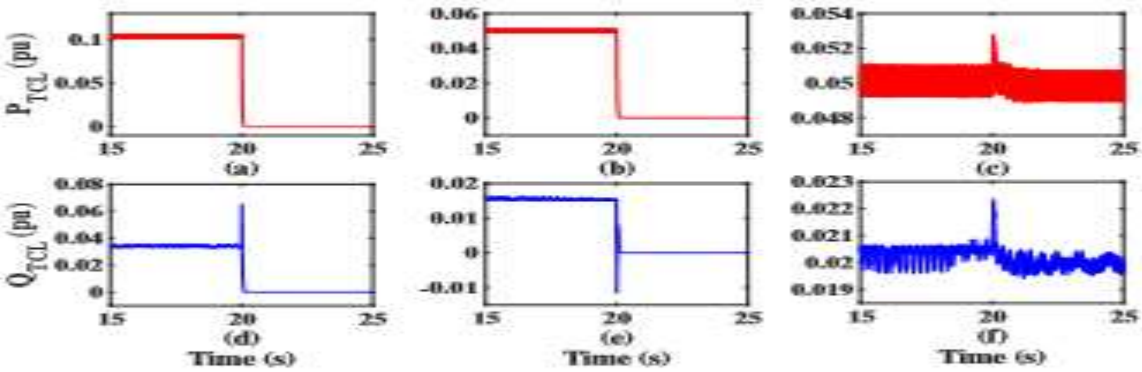


Fig. 9. Active and reactive power of TCLs in three phases. Phase A: (a) and (d). Phase B: (b) and (e). Phase C: (c) and (f).

B. Capability of PV Inverter to Mitigate VUF

In this section, the PV inverter negative sequence controller capability is examined. The TCLs are not manipulated for this case.

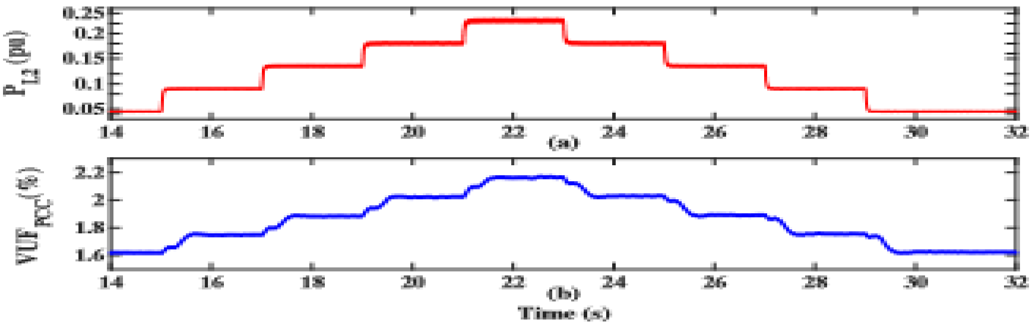
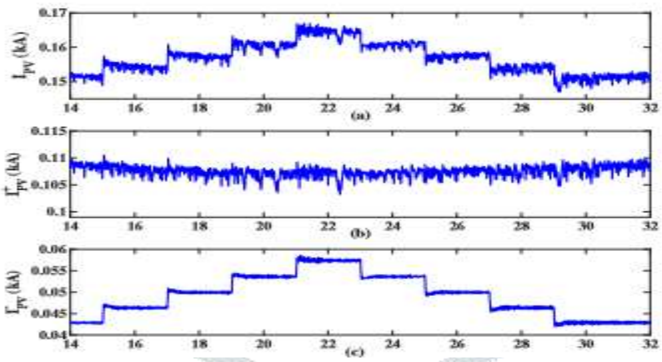


Fig. 10. PV inverter case: (a) Unbalanced load profile at L2 bus. (b) % VUF measured at PCC.



the negative sequence current of the PV inverter increased according to the unbalanced load profile while the positive sequence current reacted to the change in negative sequence current. It is to be noted that the PV inverter's negative sequence controller is also activated for VUF less than 2% as opposed to the PV control strategy presented in Fig. 3. This is done just to demonstrate the capability of the PV inverter to mitigate VU. On regulating the VU, the dc link voltage of the PV power system is not violated as shown in fig12.

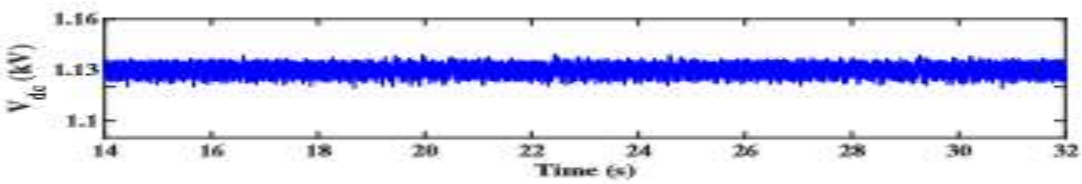


Fig. 12. DC link voltage of the PV inverter.

C. Coordination Between PV inverter and TCLs for VUF Mitigation

There might be a situation when the PV inverter current saturates, and hence cannot further compensate the negative sequence current injected into the microgrid. For such scenarios, the study proposes the manipulation of TCLs for VUF mitigation. To verify the effectiveness of the proposed VUF mitigation strategy, unbalanced loads at the bus L1 and L2 are simulated. The unbalanced load at the L2 bus is varied such that the PV inverter current reaches its saturation limit, and cannot further mitigate the VUF.

14 16 18 20 22 24 26 28 30 32 (b) Time (s) 1.4 1.6 1.8 2 2.2 VUF PCC (%)

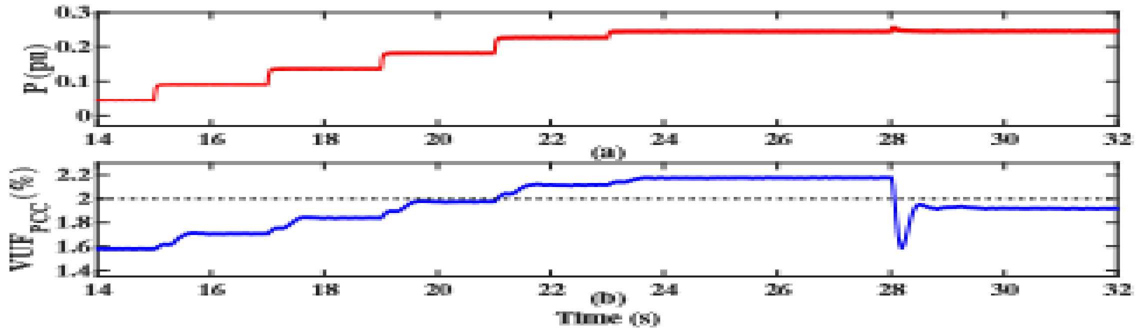


Fig. 13. Coordination case: (a) Unbalanced load profile at L2 bus. (b) % VUF measured.

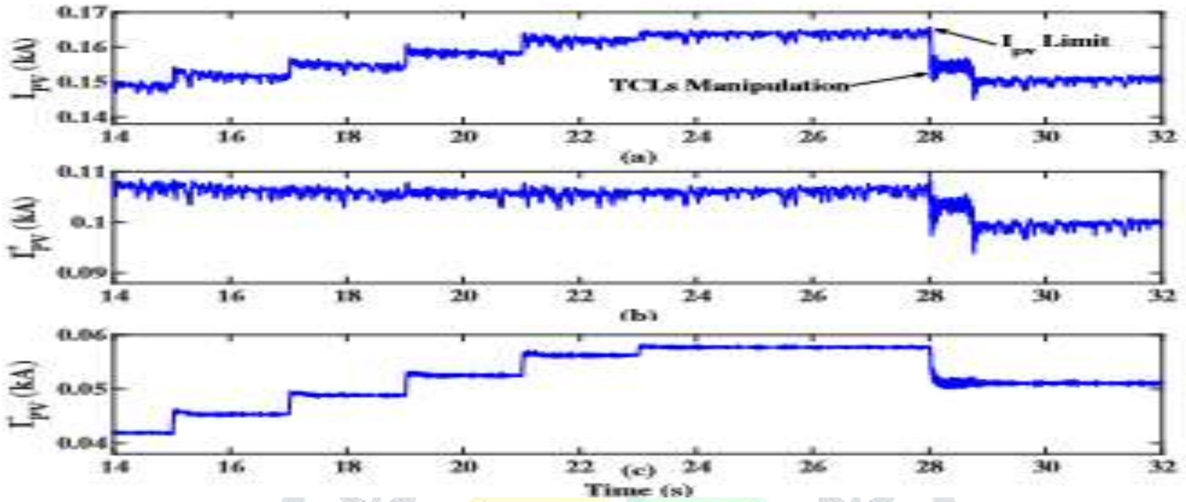


Fig.

As shown in Fig. 14 (a), the unbalanced load is increased till 24 s and kept constant. As shown in Fig. 15, the PV inverter current reached its saturation point at 24 s. The VUF at this point has crossed its limit (V UFlim = 2%). Hence, there must be another source to mitigate VUF. The TCLs are manipulated

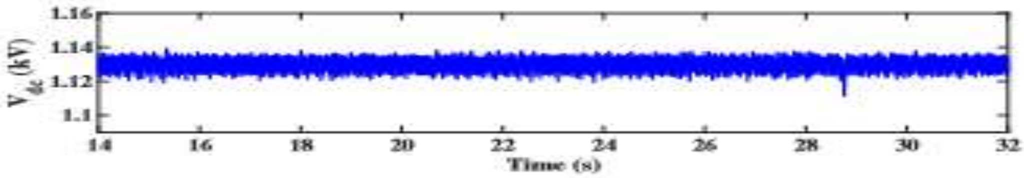


Fig. 15. Coordination case: Currents of PV inverter

at 28 s which reduced the VUF. Figs. 14 (b) and (c) show the PV inverter positive and negative sequence currents for the studied case. Because of the TCLs' manipulation, sequence currents are reduced which is positive from the aspect of preserving dynamic reactive power capacity of the inverter. The dc link voltage is well regulated during the coordination between PV inverter and TCLs for VU mitigation as shown in Fig. 16. As

Fig. 15. Coordination case: DC link voltage of the PV inverter.

explained in section V-A, the manipulation of TCLs connected to each phase relies on the deviation of phase voltage from the reference voltage. Therefore, TCLs connected on phase C are not manipulated in this case as Vc > Vref. The manipulation of TCLs decreased the difference between phase voltages as shown in Fig. 16. The power consumption of TCLs are not shown for this case as it resembles the results depicted in Section V-A. The instantaneous voltage measured at 11kV

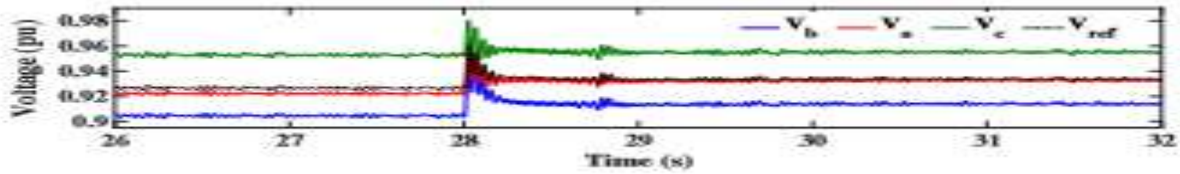


Fig. 16. Coordination case: Phase Voltages of the unbalanced load bus.

PCC, after reducing VUF by the PV inverter and the TCLs.

D. Effect of TCLs Manipulation on Frequency

The major concern about TCLs' manipulation in the proposed VUF mitigation scheme is the possibility of causing unintentionalover-frequency.Therefore, alarge amount of TCLs'

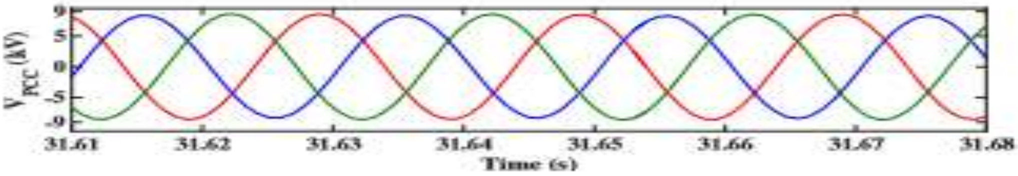
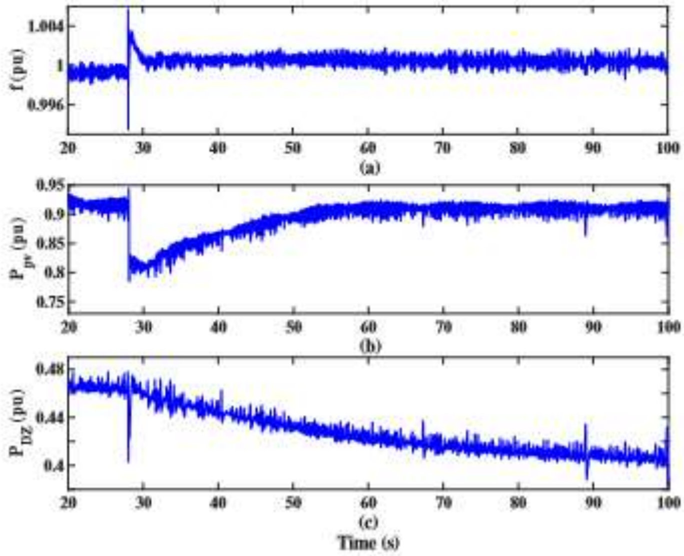


Fig. 17. Three phase AC voltage measured at PCC.

manipulation for VUF mitigation needs a detailed assessment of over-frequency regulation capability of microgrids. To enhance the over-frequency regulation capability, the PV power is curtailed in the transient state, and the operation of the PV is restored to the maximum power point tracking (MPPT) in the steady state. The PV power is curtailed based on the droop defined as PPV = {PMPPT,0} for fpu = {1.0025,1.008}. When the frequency falls below 1.001 pu because of the PV power curtailment, the operation of the PV is gradually restored to the MPPT from curtailed PV power point. This gradual return of the PV operation is coordinated with the gradual unloading of the diesel generator equipped with Pf droop controlled governor. Apparently, the PV operates or tries to operate at MPPT below 1.001 pu frequency. The details of the PV operation have been provided . The BESS active power is controlled using a P-f droop defined as PBESS,pu = {−1,1} for fpu = {1.008,0.99} as described in . As shown in Fig. 18(a), the TCLs' manipulation for VUF

Fig. 18. Effect on frequency response: (a) Frequency. (b) Active power of PV. (c) Active power of diesel generator.

mitigation at 28 s resulted in over-frequency. The PV power system curtailed its active power from 0.92 pu to 0.7806 pu in the transient state, and the PV operation gradually started to move towards the MPPT from the curtailed PV power point, whenthefrequencyfellbelow1.001puasshowninFig.18(b). The PV operation is restored to the MPPT from the curtailed PV power point at 60 s. The diesel generator is unloaded to handle the changed system loading at steady state as shown in Fig. 18(c).



Fig; effect on frequency response: (a) frequency (b) active power of PV (c) active power of diesel generator

By applying this strategy, frequency is quickly regulated in accordance , and the PV operation is released to its MPPT.

VI. REAL-TIME SIMULATIONS

The proposed strategy for mitigating VU is verified in a real-time digital simulator, OP5600-OPAL-RT. Currently the OPAL-RT does not have a PSCAD interface. Therefore, the microgrid presented in Fig. 1 is simplified and modeled in MATLAB/Simulink. The modified system has a diesel generator (3.12 MVA), a PV power system (1 MW), and TCLs which are connected to a 575 V PCC. The peak load in the system is 3 MVA out of which 25% are assumed to be TCLs. The unbalance in the system is created by loading phase A higher than phase B and C. For verification of the proposed VU mitigation scheme in OPAL-RT, the test microgrid in MATLAB is separated in a controller unit and a power system unit. Then the MATLAB model is compiled using RT-LAB to convert the model to C-language. The controller and power system units of the test microgrid are loaded in two different cores of OPAL-RT's CPU. The model in OPAL-RT is sampled at every 50μs and the desired signals are sent to 4-channel Tektronix DPO 4054B oscilloscope for monitoring through analog input/output (IO) ports of OPAL-RT. To verify the proposed control strategy, two real-time simulation cases are carried out: 1) PV inverter control for VU mitigation; and 2) Coordinated control of PV and TCLs for VU mitigation.

CONCLUSION

This paper presented a novel voltage unbalance mitigation scheme deploying generation-side inverters and demand-side management in an islanded microgrid. The PV grid-tied inverter, and TCLs are used as candidates for VU mitigation of the generation-side and the demand-side management respectively. The positive and negative sequence controller implemented in PV grid-tied inverter is developed for its balanced and unbalanced operation. In addition, a voltage dependent model of TCLs, considering the voltage dependency in its active power and reactive power consumption, is developed. This TCL model provides a ground of demand-side management for VU mitigation. The voltage unbalance mitigation capability of the PV inverter, and TCLs is established.

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