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AN ADVANCED POWER CONTROL STRATEGY AND OPTIMIZATION OF LARGE SCALE GRID CONNECTED PHOTOVOLTAIC SYSTEMS IN THE SMART GRID

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***Abstract*—** In future smart grid, DC-AC inverter based renewable energy sources will greatly participate in not only the real power generation but also reactive power compensation. Among all the renewable energy sources, grid-connected photovoltaic (PV) systems have received much attention by engineers and researchers. Grid-connected PV systems with DC-AC inverters are able to supply real power to the utility grid as well as reactive power. The real power extracted by the DC-AC inverters is usually at the maximum power point (MPP) of the attached PV arrays and the reactive power is used to compensate the grid demand. Photovoltaic (PV) power systems have become one of the most promising renewable generation technologies because of their attractive characteristics such as abundance of solar and clean energy. Battery storage is usually employed in photovoltaic (PV) system to mitigate the power fluctuations due to the characteristics of PV panels and solar irradiance. Control schemes for PV-battery systems must be able to stabilize the bus voltages as well as to control the power flows flexibly.

This project proposes a Comprehensive Control and Power Management System (CAPMS) for PV-battery-based hybrid microgrids with both AC and DC buses, for both Grid-connected and Islanded modes. The proposed CAPMS is successful in regulating the dc and ac bus voltages and frequency stably, controlling the voltage and power of each unit flexibly, and balancing the power flows in the systems automatically under different operating circumstances, regardless of disturbances from switching operating modes, fluctuations of irradiance and temperature, and change of loads. Matlab/Simulink simulations are presented in order to show the outstanding performance of the proposed design approach.

I. INTRODUCTION

In current power grid, electricity which is also considered as real power is generated by different kinds of generating units, transferred by complex transmission systems, and distributed through distribution systems to considerable loads. Many challenging problems of optimally controlling and planning real power have arisen due to the complex hierarchical structure of the power grid, extremely large amount of real power demand, the limited capability of the grid, and considerable electric components. Hence, the injection of certain amount of reactive power provides the capability to take more real power load without a voltage collapse. In current power grid, the control of voltage levels, which allow real power to be transferred, are accomplished by controlling the generation, absorption, and flow of reactive power. Real and reactive power control and optimization are always two major topics that have been studied for years for existing power grid. Distributed generation (DG) has recently received a great deal of attention as a potential solution to meet the increased demand for electricity, to reduce stress on the existing transmission system, and to incorporate more renewable and alternative energy sources. Subsequently, the microgrid concept has emerged as a promising approach to coordinate different types of distributed energy resources effectively by using local power management systems. Distributed energy resources (DER) considered in the literature are typically non conventional and renewable resources, such as fuel cells, biomass, geothermal, photovoltaic (PV), wind, and micro turbines. This is mainly due to the modular nature of these resources, and the negligible or low greenhouse gas emissions. In addition to the distributed generation (DG) resources, fast acting energy storage, such as batteries, flywheels, or super capacitors, is considered crucial to the operating of the microgrid as it facilitates voltage and frequency regulation during the islanded mode. The output voltage in most of these resources is either in DC or in unregulated AC form. Due to the unregulated output voltage, and the inherent intermittent nature of the renewable energy sources, power electronic converters are employed to control the generated power, and interface these energy sources. In the grid-connected mode, the operating voltage and frequency regulation is provided by the grid. The utility grid ensures a relatively stiff frequency regulation due to the rotating mass inertia of the large synchronous generators in the power system. Moreover, the amount of power exchanged between the microgrid and the grid is determined by the difference between the generation and the load demand in the microgrid. In other words, the grid is responsible for maintaining the power balance in the microgrid.

Photovoltaic (PV) power systems have become one of the most promising renewable generation technologies because of their attractive characteristics such as abundance of solar and clean energy. Rapid PV technology development and declining installation costs are also stimulating the increasing deployment of PV in power systems. However, due to the nature of solar energy and PV panels, instantaneous power output of a PV system depends largely on its operating environment, such as solar irradiance and surrounding temperature, resulting in constant fluctuations in the output power. Therefore, to maintain a reliable output power, battery storage systems are usually integrated with PV systems to address the variability issue. Since PV output power and load demand may change constantly during a day, the power management algorithms for PV-battery system are required to manage the power flow and promptly respond to any change to maintain the balance between power productions and consumptions. Furthermore, both DC bus and AC bus voltages must be stabilized regardless of changes in the system to ensure a reliable power supply.

It proposes a control and power management system (CAPMS) for PV-battery systems, which is a centralized control system that flexibly and effectively controls power flows among the power sources, loads, and utility grid. The proposed method succeeds in regulating the voltage on both DC and AC buses, transferring between grid-connected and islanded operating modes smoothly, and balancing power quickly in the hybrid PV-battery system.

II. SYSTEM MODELING

A typical configuration of PV-battery system is illustrated in Fig. 1, which is a hybrid microgrid system consisting of a PV array that contains a number of PV panels, battery bank for power storage, and a centralized bidirectional inverter that interfaces the DC to AC power system. A unidirectional DC/DC converter is installed to control the power of PV arrays, while the battery bank is charged/discharged by controlling a bidirectional converter that bridges the battery and the DC bus. DC loads are supplied through direct connection to the DC bus and AC loads and the point of common coupling (PCC) is located on the AC side. Before connecting to the utility grid, a transformer is employed to step up the AC voltage to that of the grid.

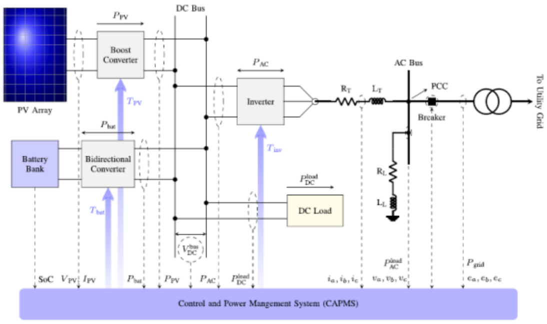


Fig:1. The proposed control and power management system (CAPMS) for PV-battery-based hybrid microgrids.

Fig.1 illustrates the configuration of a typical PV-battery system with the proposed CAPMS. In this topology, the PV array is interfaced with the DC bus by a DC/DC boost converter while the battery bank uses a bidirectional DC/DC converter to control the charging and discharging processes. A centralized inverter is installed to interconnect the DC and AC networks. DC load block generally represents the loads that are connecting at the DC bus, which can be multiple types of loads such as electric vehicles or office buildings. There are also AC loads consuming power at the AC bus. This is a typical PV battery microgrid system and similar or same configurations have been widely used and investigated. The proposed CAPMS is a centralized power management system consisting of a supervisory module that monitors the required real-time parameters (dashed lines in Fig.1) from the PV-battery system and multiple controllers for each of the power converters.

CONTROLLER DESIGN OF THE CAPMS

A. PV Array Controller

The PV array converts solar energy into DC power, and is connected to the DC bus via a boost DC/DC converter. However, due to nonlinear characteristics of PV panels and the stochastic fluctuations of solar irradiance, there is always a maximum power point (MPP) for every specific operating situation of a PV array. Therefore, maximum power point tracking (MPPT) algorithms are typically implemented in PV system to extract the maximum power a PV array can provide. The proposed CAPMS employs one of the most popular methods, the Incremental Conductance MPPT, which provides a reference voltage *V*MPPT that the PV array will track to produce the maximum power under various operation conditions (different combinations of irradiance and temperature). There are three possible control schemes for the PV array: MPPT control, power-reference control, and DC bus voltage control, depending on the situation of the PV-battery system. For example, in islanded mode, when *P*MPPT PV is greater than the total load demand (DC and AC), and the battery is fully charged or the charging rate *P*bat reaches its upper limit, the CAPMS will generate control commands P_ref_Ctrl = 1 and DC_ref_Ctrl = 0 to set the PV array to work in power reference control mode by sending PWM streams, *T*PV, to the DC/DC converter accordingly. In this case, to balance the power flows, CAPMS will decide proper power references for the PV array, *P*ref PV, according to the value of which the operating voltage of the PV array, *V*PV, will be moving between its *V*MPPT and the open-circuit voltage, *V*OC. Since the DC bus voltage is regulated by the battery converter in this situation, there will be a stable voltage at the DC bus in spite of the fluctuations in *V*PV. In MPPT mode (P_ref_Ctrl = 0 and DC_ref_Ctrl = 0), real-time PV current, *I*PV, and *V*PV are measured and sent to the MPPT module, which then provides *V*MPPT as the voltage reference for the PV array. Additionally, in islanded mode, when the battery is not available, e.g., due to faults, the PV converter has to switch to control the DC bus voltage to ensure a stable power supply to the loads on the DC bus (P_ref_Ctrl = 0 and DC_ref_Ctrl = 1). Fig.2 illustrates the controller for these three modes. Note that the situation where both P_ref_Ctrl = 1 and DC_ref_Ctrl = 1 is not applicable.

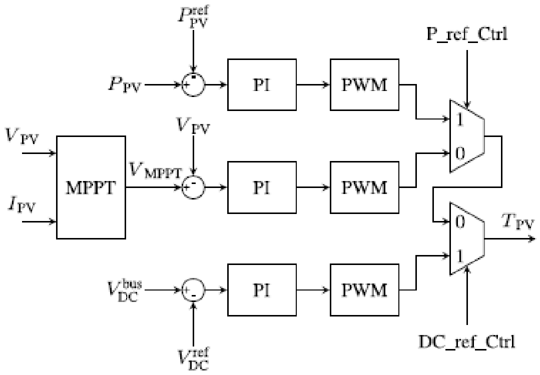


Fig:2. PV array controller.

B. Battery Controller

As an energy buffer, battery bank is necessary in PV systems for power balancing. The battery bank of this system is connected to the DC bus and is controlled by a bidirectional DC/DC converter (Fig.3) which includes two switches, *T*1 and *T*2, that control the charging/discharging process. Fig.4 explains the detailed control process. In grid-connected mode, with the command DC_ref_Ctrl = 0, the converter controls the power flow (*P*bat) in or out of the battery, where in discharging mode *P*bat > 0, and in charging mode *P*bat < 0. The final output of the battery controller is a two-dimensional switching signal *T*bat(*g*1, *g*2). In Islanded mode, the control command DC_ref_Ctrl is set to "1" by the CAPMS, which switches the converter to work in voltage reference mode. The output voltage of converter, which is also the DC bus voltage, is regulated to follow the reference so that the DC load voltage is stabilized. The CAPMS monitors the SoC of the battery and enforces its upper and lower limits (SoC upper limit = 90% and SoC lower limit = 10% in this study) in order to increase the life cycle. Note that the selections of the SoC limits do not affect the performance of the controller.

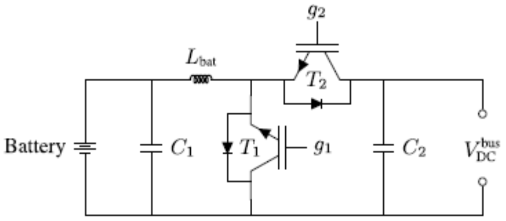


Fig:3. Bidirectional DC/DC converter for the battery bank.

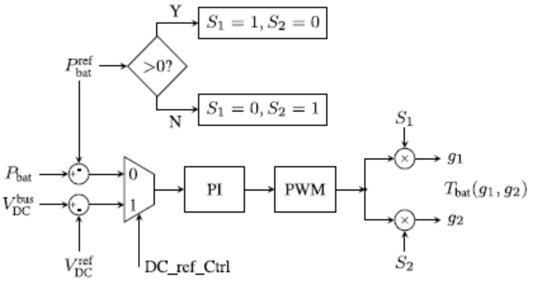


Fig:4. Battery charging/discharging controller.

C. Inverter Controller

A three-phase inverter is used to convert DC to AC power, interfacing the DC and AC sides. Similar to the converters discussed above, the control scheme of inverter depends on the operating (grid-connected or islanded) mode of the system. As is illustrated in Fig.1 and 5, in grid-connected mode, a phase-locked loop (PLL block) is employed to extract θ, angle the of phase-A voltage after the breaker(*ea*). In islanded mode, θ is generated locally, which is periodical ramp signal varying from 0 to 2π with frequency f . It is used to decompose the three-phase AC bus voltages (*va*, *vb* and *vc*) and the inverter output currents (*ia*, *ib* and *ic*) into d-q frame variables *Vd* and *Vq*, and *Id* and *Iq* by Park transformation, respectively, for control purposes.

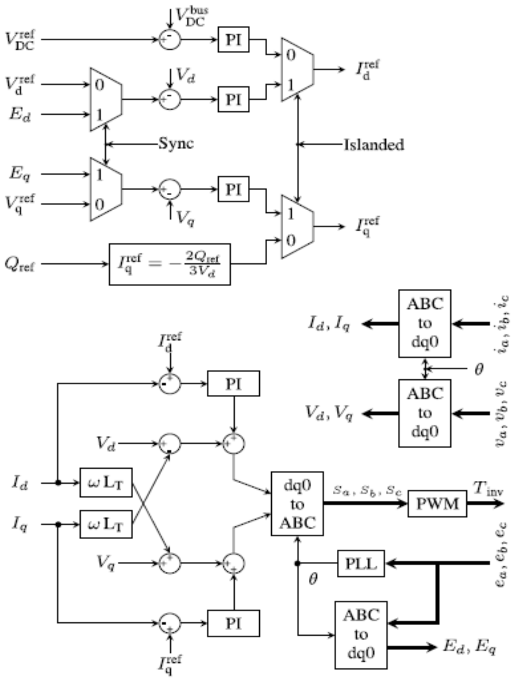


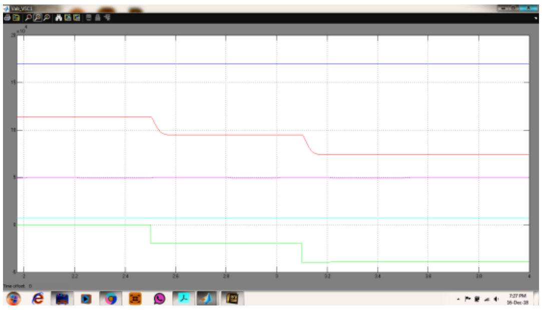
Fig:5. Control scheme of the inverter.

Depending on the operating mode, the controller selects different sets of variables to be controlled. Under islanded mode, CAPMS sets the signal “Islanded” to 1, forcing the converter to regulate the AC bus voltage *Vd* and *Vq*. Frequency of the AC bus voltages (*f*) is set to 60 Hz in a open-loop manner. Before closing the breaker and reconnecting the PV-battery system to the grid, the AC bus voltage must be synchronized with the grid. During islanded mode, the signal “Sync” is set to 0 so that CAPMS has full control of the AC bus voltage by adjusting the references, *V*ref d and *V*ref q . However, to ensure a smooth transition upon switching to grid-connected mode, “Sync” will be set to 1 to synchronize the AC bus and grid side voltages right before closing the breaker. To this end, θ will be synchronized to follow the output angle of PLL, and the AC voltages after the breaker in d-q frame, *Ed* and *Eq*, will be chosen as the references for *Vd* and *Vq* (Fig. 5), respectively. In grid-connected mode (Islanded = 0), the inverter is responsible for regulating the DC bus voltage *V*DC and controlling the reactive power transferring from DC to AC side. Additionally, in both operating modes, the current references of inner loop of the controller (*I*ref d and *I*ref q) can be enforced to proper limits to prevent overloading of the inverter.

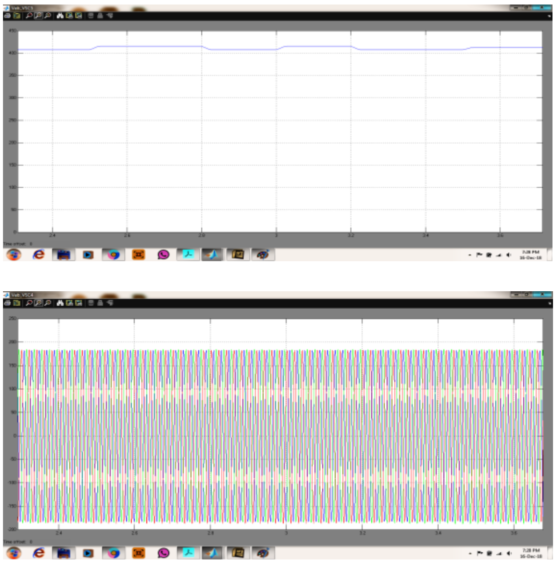
III. SIMULATION RESULTS

In order to verify the performance of the proposed CAPMS, numerous simulation case studies are carried out in this section using the Matlab/Simulink.

A. Simulation Verification: Grid-Connected Mode



(a) power flows



(b) Voltage values of the PV-battery system
Fig:6. Grid-connected mode Case A-1

The first case is the normal operation situation of the PV-battery system in grid-connected mode, when the battery is fully available for power balancing (10% < SoC < 90%). PV array is working in MPPT mode, tracking the voltage reference (*V*MPPT) estimated by the MPPT module. DC and AC loads are supplied by the buses. Depending on the amount of generation, load, and demand requested by the grid (*P*grid), the battery is balancing the power by absorbing or releasing power. Fig. 6 presents the power flows and voltages of the PV-battery system under the control of CAPMS in Case A-1. Before 2.6 s, the PV array power *P*PV is around 170kW in MPPT mode, which is shared by the DC load (*P*load DC = 50 kW), AC load (*P*load AC = 10 kW), and the utility grid (*P*grid = 110 kW). The power flow in or out of the battery during this period is about 0 since no extra power is available. At about 2.6 s, as the grid demand decreases to around 85kW, 15kW extra power is sent to charge the battery (*P*bat = 15 kW). Later at 3.15 s, the grid demand drops again, and the battery power continues to increase. As long as the battery SoC and *P*bat are within the limits, the battery is able to balance the power as an energy buffer. During these changes, the DC and AC bus voltages are controlled (Fig. 6).

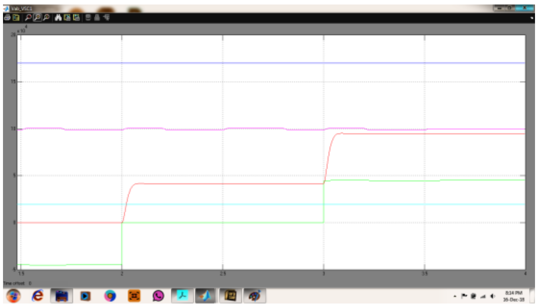
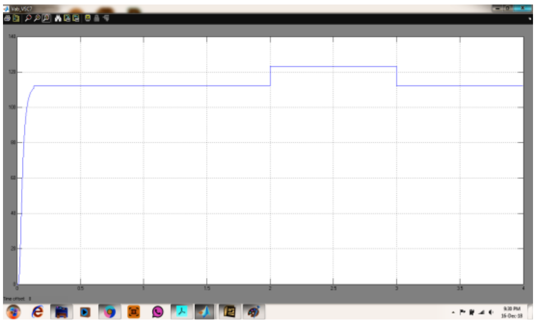


Fig:7. Grid-connected mode Case A-2: power flows of the PV-battery system.

As the battery is charged, the SoC will keep increasing. When the battery SoC is greater than 90 %, CAPMS 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 complement the change. Fig. 7 illustrates these processes. At 2 s, the battery is fully charged and the CAPMS sets *P*ref bat to 0. Thereby, *P*bat follows the reference and the excess power of the system is delivered to the grid (*P*grid increases to 50kW at 2 s). At 3 s, the demand from grid (*P*demand grid) increases to about 95kW. Since the PV array is working in MPPT mode (*PPV* = 170 kW), and the DC and AC loads require 125kW totally (*P*Load DC = 103kW and *P*Load AC = 22 kW), the battery has to be controlled to provide 50kW to balance the power.

Fig:8. Grid-connected mode Case A-3-1: PV array in power-reference mode.

There is also situation where the SoC of battery has reached the upper limits (90%), however, the maximum power provided by the PV array is more than the demands and loads. In this case, since the battery has been fully charged, and if the grid cannot absorb the excess power from PV array, CAPMS will switch the operating mode of PV from MPPT to power-reference mode to balance the system, as is presented in Fig. 8 (Case A-3-1). Before 2 s, *PPV* is set to 150kW, and *P*bat is set to 0. Therefore, besides the DC and AC load, (50 and 25kW, respectively), excess power is sent to the grid (*P*grid = 75 kW). As the reference of PV power changes at 2 s and 3 s, the power sent to grid adapts accordingly, keeping the power balanced in the PV-battery system.



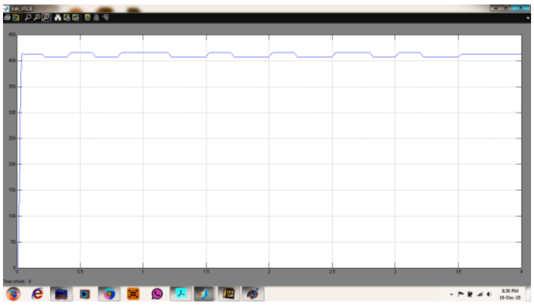


Fig:9. Grid-connected mode Case A-3-2: DC bus and PV array voltages during transitions between MPPT and power-reference modes.

Fig. 9 (Case A-3-2) shows the smooth changes of PV voltage and the stable DC bus voltage during the transitions between MPPT and power-reference modes. Note that *VPV* is greater than *V*MPPT but less than *V*OC in power-reference mode, and the PV operating point depends on the value of *P*ref PV.

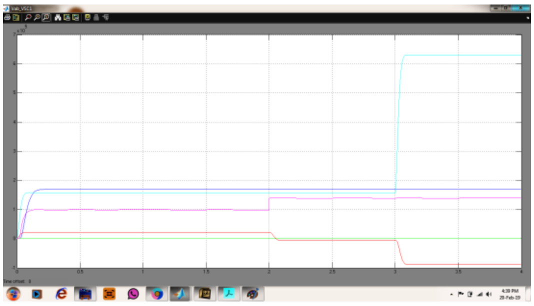


Fig.10. Grid-connected mode Case A-4: the PV-battery system is receiving power from the grid after 2.2 s.

The power flow in the inverter is bidirectional, i.e., when necessary, the PV-battery system can request power from the grid. For instance, when there is available power from the grid and the PV-battery system has more demand than generation, the CAPMS can reverse the power through the inverter to supply the system. Fig. 10 gives an example of this situation. The battery SoC is less than 10% which hits the lower limit and stops releasing power for battery protection. The

PV array is supplying power to the DC and AC loads and the grid. However, DC load increases suddenly at 2 s, which causes the DC system to request power from the grid. Hence, *P*grid becomes negative, delivering reversed power in the inverter from the grid to the DC load. Immediately after that, at 3 s, the AC load increases. Since the battery bank is still not available, power from the grid increases to balance the system. Case study A-4 shows the proposed CAPMS rapidly responds to this situation.

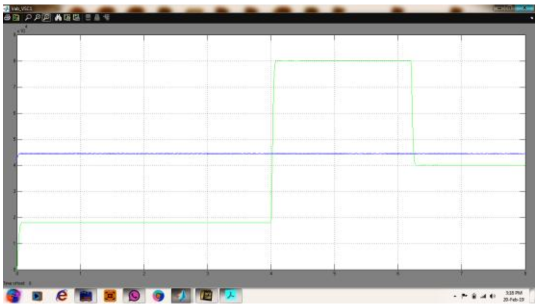


Fig.11. Grid-connected mode Case A-5: Reactive power control of the inverter.

In grid-connected mode, since the inverter has full control of the DC bus voltage as well as the reactive power, it is able to provide reactive power to the grid if necessary. The waveforms associated with this case are plotted in Fig. 11, where the blue and red curves are the active and reactive power, *P*grid and *Q*grid, respectively that are being transferred from the PV-battery system to the grid. The inverter controls the reactive power flexibly. Regardless of changes of *Q*grid, *P*grid is stabilized at its value.

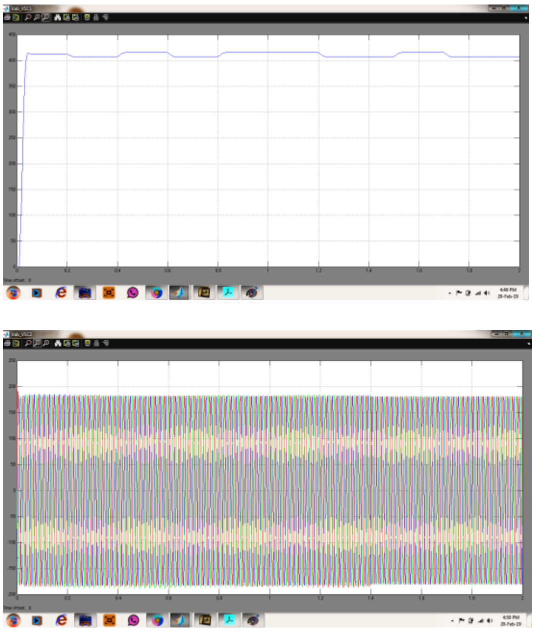


Fig.12. Grid-connected mode Case A-6: transition from grid-connected to islanded mode.

As is mentioned in previous sections, the PV battery system may work in either grid-connected or islanded modes. For example, when the utility grid is unstable or there are severe faults at the AC bus, to prevent drawing backfeeding current from the grid, the circuit breaker at PCC will open, switching the system to work in islanded mode. After operating the breaker, the inverter is switched to control the AC bus voltage and frequency, while the DC bus voltage is controlled by the battery converter. Fig. 12 presents the dynamics of the DC and AC bus voltages (operating mode is changed at 1.4 s), where the voltages take less than 0.05 s to settle.

IV. CONCLUSION

It proposes a control and power management system (CAPMS) for hybrid PV-battery systems with both DC and AC buses and loads, in both grid-connected and islanded modes. The presented CAPMS is able to manage the power flows in the converters of all units flexibly and effectively, and ultimately to realize the power balance between the hybrid microgrid system and the grid. Furthermore, CAPMS ensures a reliable power supply to the system when PV power fluctuates due to unstable irradiance or when the PV array is shut down due to faults. DC and AC buses are under full control by the CAPMS in both grid-connected and islanded modes, providing a stable voltage environment for electrical loads even during transitions between these two modes. This also allows additional loads to access the system without extra converters, reducing operation and control costs.

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