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A Grid-Connected Dual Voltage Source Inverter with Power Quality Improvement Features

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Abstract

This paper presents a dual voltage source inverter (DVSI) scheme to enhance the power quality and reliability of the microgrid system. The proposed scheme is comprised of two inverters, which enables the microgrid to exchange power generated by the distributed energy resources (DERs) and also to compensate the local unbalanced and nonlinear load. The con- trol algorithms are developed based on instantaneous symmetrical component theory (ISCT) to operate DVSI in grid sharing and grid injecting modes. The proposed scheme has increased reliability, lower bandwidth requirement of the main inverter, lower cost due to reduction in filter size, and better utilization of micro- grid power while using reduced dc-link voltage rating for the main inverter. These features make the DVSI scheme a promising option for microgrid supplying sensitive loads. The topology and control algorithm are validated through extensive simulation and experimental results.

Keywords: Grid-connected inverter, instantaneous symmetrical component theory (ISCT), microgrid, power quality.

INTRODUCTION:

TECHNOLOGICAL progress and environmental concerns drive the power system to a paradigm shift with more renewable energy sources integrated to the network by means of distributed generation (DG). These DG units with coordi- nated control of local generation and storage facilities form a microgrid. In a microgrid, power from different renewable energy sources such as fuel cells, photovoltaic (PV) systems, and wind energy systems are interfaced to grid and loads using power electronic converters. A grid interactive inverter plays an important role in exchanging power from the microgrid to the grid and the connected load [2], [3]. This microgrid inverter can either work in a grid sharing mode while supplying a part of local load or in grid injecting mode, by injecting power to the main grid.

Maintaining power quality is another important aspect whichhas to be addressed while the microgrid system is connected to the main grid. The proliferation of power electronics devices and electrical loads with unbalanced nonlinear currents has degraded the power quality in the power distribution net- work. Moreover, if there is a considerable amount of feeder impedance in the distribution systems, the propagation of these harmonic currents distorts the voltage at the point of common coupling (PCC). At the same instant, industry automation has reached to a very high level of sophistication, where plants like automobile manufacturing units, chemical factories, and semiconductor industries require clean power. For these appli- cations, it is essential to compensate nonlinear and unbalanced load currents [4].

Load compensation and power injection using grid interac- tive inverters in microgrid have been presented in the literature [5], [6]. A single inverter system with power quality enhance- ment is discussed in [7]. The main focus of this work is to realize dual functionalities in an inverter that would provide the active power injection from a solar PV system and also works as an active power filter, compensating unbalances and the reactive power required by other loads connected to the system.

In [8], a voltage regulation and power flow control scheme for a wind energy system (WES) is proposed. A distribu- tion static compensator (DSTATCOM) is utilized for voltage regulation and also for active power injection. The control scheme maintains the power balance at the grid terminal during the wind variations using sliding mode control. A multifunc- tional power electronic converter for the DG power system is described in [9]. This scheme has the capability to inject power generated by WES and also to perform as a harmonic compen- sator. Most of the reported literature in this area discuss the topologies and control algorithms to provide load compensa- tion capability in the same inverter in addition to their active power injection. When a grid-connected inverter is used for active power injection as well as for load compensation, the inverter capacity that can be utilized for achieving the second objective is decided by the available instantaneous microgrid real power [10]. Considering the case of a grid-connected PV inverter, the available capacity of the inverter to supply the reactive power becomes less during the maximum solar insolation periods. At the same instant, the reactive power to regulate the PCC voltage is very much needed during this period. It indicates that providing multi functionalities in a single inverter degrades either the real power injection or the load compensation capabilities.

This paper demonstrates a dual voltage source inverter (DVSI) scheme, in which the power generated by the microgrid is injected as real power by the main voltage source inverter (MVSI) and the reactive, harmonic, and unbalanced load compensation is performed by auxiliary voltage source inverter (AVSI). This has an advantage that the rated capacity of MVSI can always be used to inject real power to the grid, if sufficient renewable power is available at the dc link. In the DVSI scheme, as total load power is supplied by two inverters, power losses across the semiconductor switches of each inverter are reduced. This increases its reliability as compared to a single inverter with multifunctional capabilities. Also, smaller size modular inverters can operate at high switching frequencies with a reduced size of interfacing inductor, the filter cost gets reduced. Moreover, as the main inverter is supplying real power, the inverter has to track the fundamental positive sequence of current. This reduces the bandwidth requirement of the main inverter. The inverters in the proposed scheme use two separate dc links. Since the auxiliary inverter is supplying zero sequence of load current, a three-phase three-leg inverter topology with a single dc storage capacitor can be used for the main inverter. This in turn reduces the dc-link voltage requirement of the main inverter. Thus, the use of two separate inverters in the proposed DVSI scheme provides increased reliability, better utilization of microgrid power, reduced dc grid voltage rating, less bandwidth requirement of the main inverter, and reduced filter size. Control algorithms are developed by instantaneous symmetrical component theory (ISCT) to operate DVSI in grid-connected mode, while con- sidering nonstiff grid voltage. The extraction of fundamental positive sequence of PCC voltage is done by dq0 transformation. The control strategy is tested with two parallel inverters connected to a three-phase four-wire distribu- tion system. Effectiveness of the proposed control algorithm is validated through detailed simulation and experimental results.

FACTS

Flexible AC Transmission Systems, called FACTS, got in the recent years a well known term for higher controllability in power systems by means of power electronic devices. Several FACTS-devices have been introduced for various applications worldwide. A number of new types of devices are in the stage of being introduced in practice. In most of the applications the controllability is used to avoid cost intensive or landscape requiring extensions of power systems, for instance like upgrades or additions of substations and power lines. FACTS-devices provide a better adaptation to varying operational conditions and improve the usage of existing installations.

Figure 1.1 shows the basic idea of FACTS for transmission systems. The usage of lines for active power transmission should be ideally up to the thermal limits. Voltage and stability limits shall be shifted with the means of the several different FACTS devices. It can be seen that with growing line length, the opportunity for FACTS devices gets more and more important. The influence of FACTS-devices is achieved through switched or controlled shunt compensation, series compensation or phase shift control. The devices work electrically as fast current, voltage or impedance controllers. The power electronic allows very short reaction times down to far below one second.

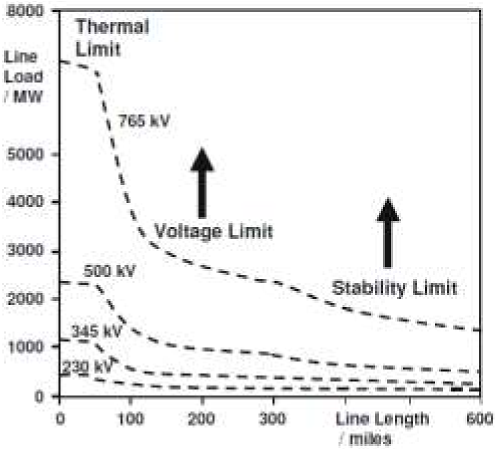


Figure 1: Operational limits of transmission lines for different voltage levels

The development of FACTS-devices has started with the growing capabilities of power electronic components. Devices for high power levels have been made available in converters for high and even highest voltage levels. The overall starting points are network elements influencing the reactive power or the impedance of a part of the power system. For the FACTS side the taxonomy in terms of 'dynamic' and 'static' needs some explanation. The term 'dynamic' is used to express the fast controllability of FACTS-devices provided by the power electronics. This is one of the main differentiation factors from the conventional devices. The term 'static' means that the devices have no moving parts like mechanical switches to perform the dynamic controllability. Therefore most of the FACTS-devices can equally be static and dynamic.

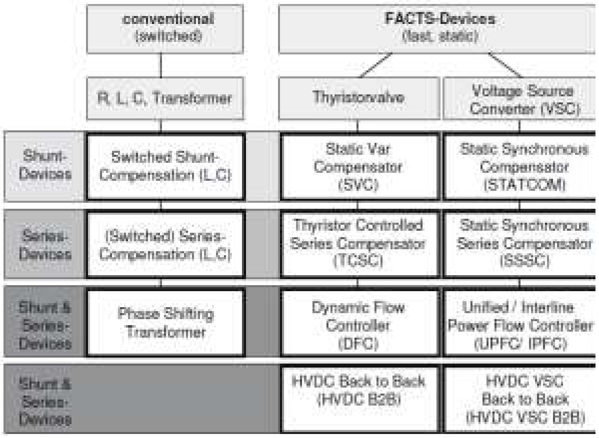


Figure 2: Overview of major FACTS-Devices

The left column in Figure 2 contains the conventional devices build out of fixed or mechanically switch able components like resistance, inductance or capacitance together with transformers. The FACTS-devices contain these elements as well but use additional power electronic valves or converters to switch the elements in smaller steps or with switching patterns within a cycle of the alternating current. The left column of FACTS-devices uses Thyristor valves or converters. These valves or converters are well known since several years. They have low losses because of their low switching frequency of once a cycle in the converters or the usage of the Thyristors to simply bridge impedances in the valves.

The right column of FACTS-devices contains more advanced technology of voltage source converters based today mainly on Insulated Gate Bipolar Transistors (IGBT) or Insulated Gate Commutated Thyristors (IGCT). Voltage Source Converters provide a free controllable voltage in magnitude and phase due to a pulse width modulation of the IGBTs or IGCTs. High modulation frequencies allow to get low harmonics in the output signal and even to compensate disturbances coming from the network. The disadvantage is that with an increasing switching frequency, the losses are increasing as well. Therefore special designs of the converters are required to compensate this.

STATCOM:

In 1999 the first SVC with Voltage Source Converter called STATCOM (STATic COMpensator) went into operation. The STATCOM has a characteristic similar to the synchronous condenser, but as an electronic device it has no inertia and is superior to the synchronous condenser in several ways, such as better dynamics, a lower investment cost and lower operating and maintenance costs. A STATCOM is build with Thyristors with turn-off capability like GTO or today IGCT or with more and more IGBTs. The static line between the current limitations has a certain steepness determining the control characteristic for the voltage.

The advantage of a STATCOM is that the reactive power provision is independent from the actual voltage on the connection point. This can be seen in the diagram for the maximum currents being independent of the voltage in comparison to the SVC. This means, that even during most severe contingencies, the STATCOM keeps its full capability. In the distributed energy sector the usage of Voltage Source Converters for grid interconnection is common practice today. The next step in STATCOM development is the combination with energy storages on the DC-side. The performance for power quality and balanced network operation can be improved much more with the combination of active and reactive power.

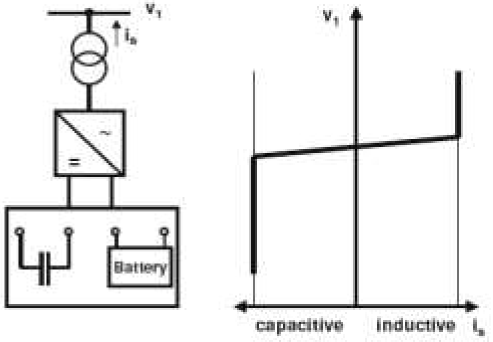
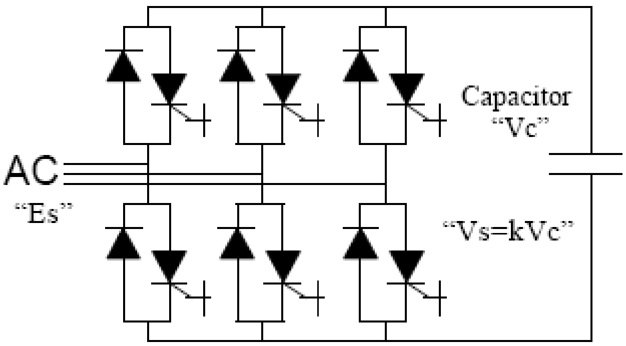


Figure 3: Statcom

STATCOM structure and voltage / current characteristic

STATCOMs are based on Voltage Sourced Converter (VSC) topology and utilize either Gate-Turn-off Thyristors (GTO) or Isolated Gate Bipolar Transistors (IGBT) devices. The STATCOM is a very fast acting, electronic equivalent of a synchronous condenser. If the STATCOM voltage, Vs, (which is proportional to the dc bus voltage Vc) is larger than bus voltage, Es, then leading or capacitive VARS are produced. If Vs is smaller then Es then lagging or inductive VARS are produced.



6 Pulses STATCOM

The three phases STATCOM makes use of the fact that on a three phase, fundamental frequency, steady state basis, and the instantaneous power entering a purely reactive device must be zero. The reactive power in each phase is supplied by circulating the instantaneous real power between the phases. This is achieved by firing the GTO/diode switches in a manner that maintains the phase difference between the ac bus voltage ES and the STATCOM generated voltage VS. Ideally it is possible to construct a device based on circulating instantaneous power which has no energy storage device (ie no dc capacitor). A practical STATCOM requires some amount of energy storage to accommodate harmonic power and ac system unbalances, when the instantaneous real power is non-zero. The maximum energy storage required for the STATCOM is much less than for a TCR/TSC type of SVC compensator of comparable rating.

STATCOM Equivalent Circuit

Several different control techniques can be used for the firing control of the STATCOM. Fundamental switching of the GTO/diode once per cycle can be used. This approach will minimize switching losses, but will generally utilize more complex transformer topologies. As an alternative, Pulse Width Modulated (PWM) techniques, which turn on and off the GTO or IGBT switch more than once per cycle, can be used. This approach allows for simpler transformer topologies at the expense of higher switching losses. The 6 Pulse STATCOM using fundamental switching will of course produce the 6 N□1 harmonics. There are a variety of methods to decrease the harmonics. These methods include the basic 12 pulse configuration with parallel star / delta transformer connections, a complete elimination of 5th and 7th harmonic current using series connection of star/star and star/delta transformers and a quasi 12 pulse method with a single star-star transformer, and two secondary windings, using control of firing angle to produce a 30□phase shift between the two 6 pulse bridges. This method can be extended to produce a 24 pulse and a 48 pulse STATCOM, thus eliminating harmonics even further. Another possible approach for harmonic cancellation is a multi-level configuration which allows for more than one switching element per level and therefore more than one switching in each bridge arm. The ac voltage derived has a staircase effect, dependent on the number of levels. This staircase voltage can be controlled to eliminate harmonics. In order to visualize the steady state operating range of the DFC, we assume an inductance in parallel representing parallel transmission paths. The overall control objective in steady state would be to control the distribution of power flow between the branch with the DFC and the parallel path. This control is accomplished by control of the injected series voltage.

The PST (assuming a quadrature booster) will inject a voltage in quadrature with the node voltage. The controllable reactance will inject a voltage in quadrature with the throughput current. Assuming that the power flow has a load factor close to one, the two parts of the series voltage will be close to collinear. However, in terms of speed of control, influence on reactive power balance and effectiveness at high/low loading the two parts of the series voltage has quite different characteristics. The steady state control range for loadings up to rated current, where the x-axis corresponds to the throughput current and the y-axis corresponds to the injected series voltage.

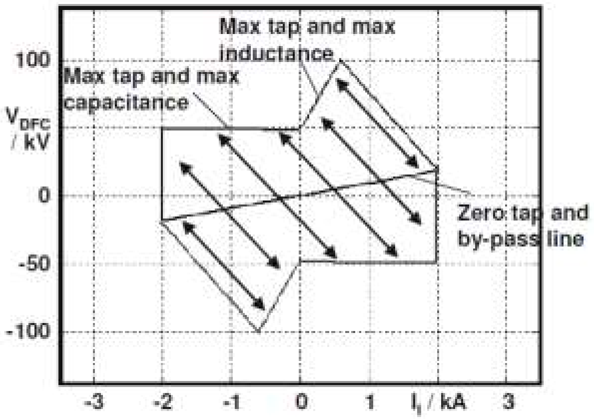


Figure 4: Operational diagram of a DFC

Operation in the first and third quadrants corresponds to reduction of power through the DFC, whereas operation in the second and fourth quadrants corresponds to increasing the power flow through the DFC. The slope of the line passing through the origin (at which the tap is at zero and TSC / TSR are bypassed) depends on the short circuit reactance of the PST. Starting at rated current (2 kA) the short circuit reactance by itself provides an injected voltage (approximately 20 kV in this case). If more inductance is switched in and/or the tap is increased, the series voltage increases and the current through the DFC decreases (and the flow on parallel branches increases). The operating point moves along lines parallel to the arrows in the figure. The slope of these arrows depends on the size of the parallel reactance. The maximum series voltage in the first quadrant is obtained when all inductive steps are switched in and the tap is at its maximum.

Now, assuming maximum tap and inductance, if the throughput current decreases (due e.g. to changing loading of the system) the series voltage will decrease. At zero current, it will not matter whether the TSC / TSR steps are in or out, they will not contribute to the series voltage. Consequently, the series voltage at zero current corresponds to rated PST series voltage. Next, moving into the second quadrant, the operating range will be limited by the line corresponding to maximum tap and the capacitive step being switched in (and the inductive steps by-passed). In this case, the capacitive step is approximately as large as the short circuit reactance of the PST, giving an almost constant maximum voltage in the second quadrant.

Unified Power Flow Controller:

The UPFC is a combination of a static compensator and static series compensation. It acts as a shunt compensating and a phase shifting device simultaneously.

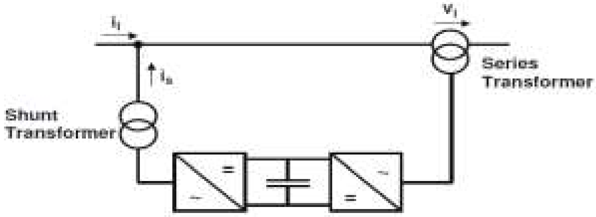
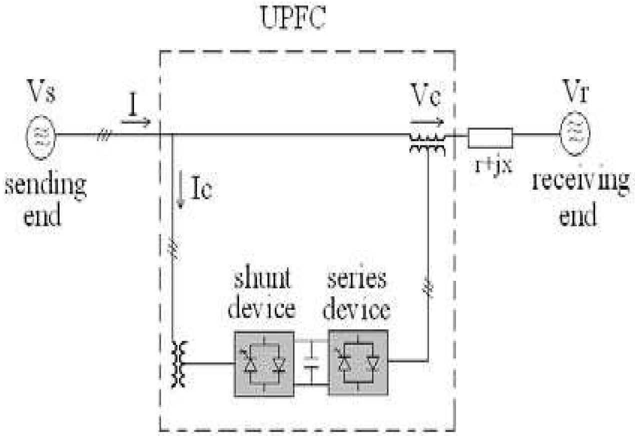


Figure 5: Principle configuration of an UPFC

The UPFC consists of a shunt and a series transformer, which are connected via two voltage source converters with a common DC-capacitor. The DC-circuit allows the active power exchange between shunt and series transformer to control the phase shift of the series voltage. This setup, as shown in Figure 1.21, provides the full controllability for voltage and power flow. The series converter needs to be protected with a Thyristor bridge. Due to the high efforts for the Voltage Source Converters and the protection, an UPFC is getting quite expensive, which limits the practical applications where the voltage and power flow control is required simultaneously.

OPERATING PRINCIPLE OF UPFC

The basic components of the UPFC are two voltage source inverters (VSIs) sharing a common dc storage capacitor, and connected to the power system through coupling transformers. One VSI is connected to in shunt to the transmission system via a shunt transformer, while the other one is connected in series through a series transformer.



The series inverter is controlled to inject a symmetrical three phase voltage system (Vse), of controllable magnitude and phase angle in series with the line to control active and reactive power flows on the transmission line. So, this inverter will exchange active and reactive power with the line. The reactive power is electronically provided by the series inverter, and the active power is transmitted to the dc terminals. The shunt inverter is operated in such a way as to demand this dc terminal power (positive or negative) from the line keeping the voltage across the storage capacitor Vdc constant. So, the net real power absorbed from the line by the UPFC is equal only to the losses of the inverters and their transformers. The remaining capacity of the shunt inverter can be used to exchange reactive power with the line so to provide a voltage regulation at the connection point.

The two VSI's can work independently of each other by separating the dc side. So in that case, the shunt inverter is operating as a STATCOM that generates or absorbs reactive power to regulate the voltage magnitude at the connection point. Instead, the series inverter is operating as SSSC that generates or absorbs reactive power to regulate the current flow, and hence the power low on the transmission line. The UPFC has many possible operating modes. In particular, the shunt inverter is operating in such a way to inject a controllable current, ish into the transmission line. The shunt inverter can be controlled in two different modes:

VAR Control Mode: The reference input is an inductive or capacitive VAR request. The shunt inverter control translates the var reference into a corresponding shunt current request and adjusts gating of the inverter to establish the desired current. For this mode of control a feedback signal representing the dc bus voltage, Vdc, is also required. Automatic Voltage Control Mode: The shunt inverter reactive current is automatically regulated to maintain the transmission line voltage at the point of connection to a reference value. For this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt coupling transformer.

The series inverter controls the magnitude and angle of the voltage injected in series with the line to influence the power flow on the line. The actual value of the injected voltage can be obtained in several ways. Direct Voltage Injection Mode: The reference inputs are directly the magnitude and phase angle of the series voltage. Phase Angle Shifter Emulation mode: The reference input is phase displacement between the sending end voltage and the receiving end voltage. Line Impedance Emulation mode: The reference input is an impedance value to insert in series with the line impedance. Automatic Power Flow Control Mode: The reference inputs are values of P and Q to maintain on the transmission line despite system changes.

EXPERIMENTAL RESULTS:

The performance of the proposed DVSI is verified with experimental studies. A digital signal processor (DSP)-based prototype of DVSI as shown in Fig. 11 has been developed in the laboratory. The experimental system parameters are given in Table II. The setup consists of two 10 kVA SEMIKRON build two-level inverter for realizing AVSI and MVSI. A DSP TMS320F28335 is used to process the data in digital domain with a sampling time of 19.5 µs. The signal and logic level circuit consist of Hall effect voltage and current transducers, signal conditioning, and protection circuits along with isolated dc power supplies. A real time algorithm has been implemented in code composer studio (CCS) on the host computer. The DSP acquires the signals and processes them to generate reference currents for AVSI and MVSI. The switching commands gener- ated by the DSP are then issued to inverters through its general purpose input and output ports.

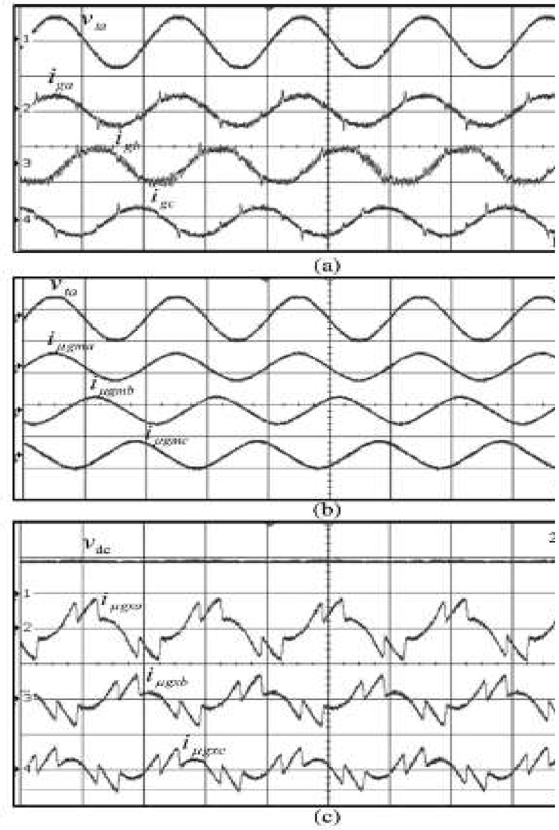


Figure 6: (a) Pcc voltage (phase-α) and grid currents after components; (b) MVSI currents; and (c) Dc-Link voltage and AVSI currents.

Tests are conducted to verify the operation of DVSI dur- ing steady state as well as transient with a sudden load change. The three-phase PCC voltages ($v_{t(abc)}$) are shown in Fig. 12. From these distorted PCC voltages, fundamental positive sequence voltages are extracted using the algorithm explained in Section III-A. These voltages are further used for realizing AVSI and MVSI reference currents. A software PLL which is implemented in DSP is being used for this extraction. The reference power of MVSI ($P_{\mu g}$) has been set at 300 W. The total unbalanced and nonlinear load consid- ered in this study take an average real power of 500 W and a reactive power of 260 VAr. The phase-*a* PCC voltage and three phase load currents before compensation. It indicates that the compensated grid currents become balanced sinusoidal and are in phase with the respective PCC voltages. Fig. 14(b) represents MVSI cur- rents and Fig. 14(c) shows dc-link voltage and AVSI currents. From these two figures, it is observed that MVSI currents are balanced sinusoidal and at unity power factor with respective PCC voltages and AVSI supplies the unbalance, harmonic, and reactive components of load currents.

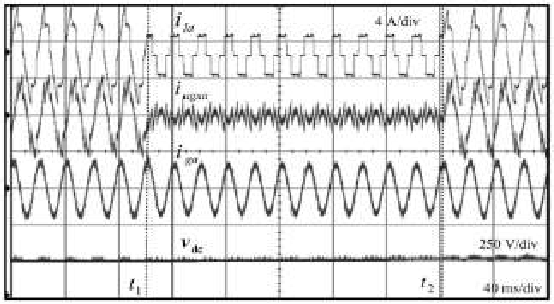


Figure 7: Experimental results: dynamics performance of AVSI during load change

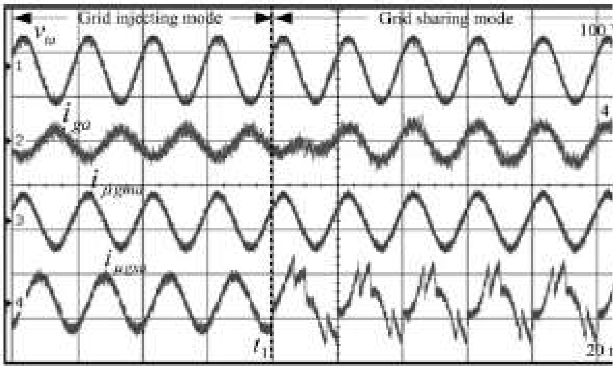
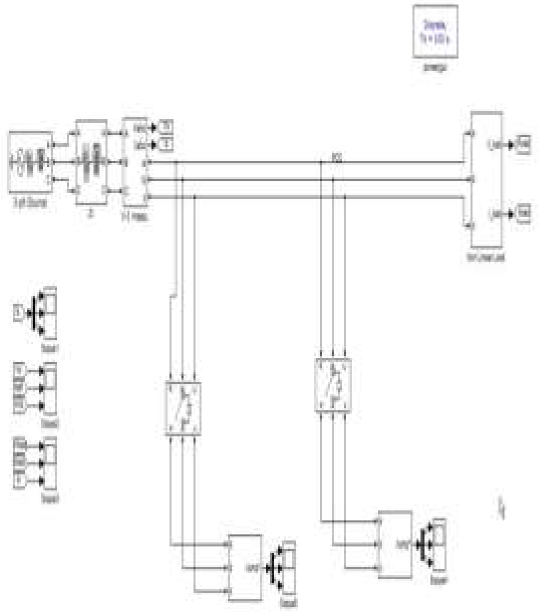
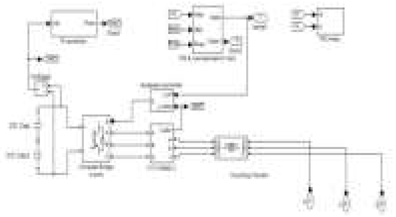


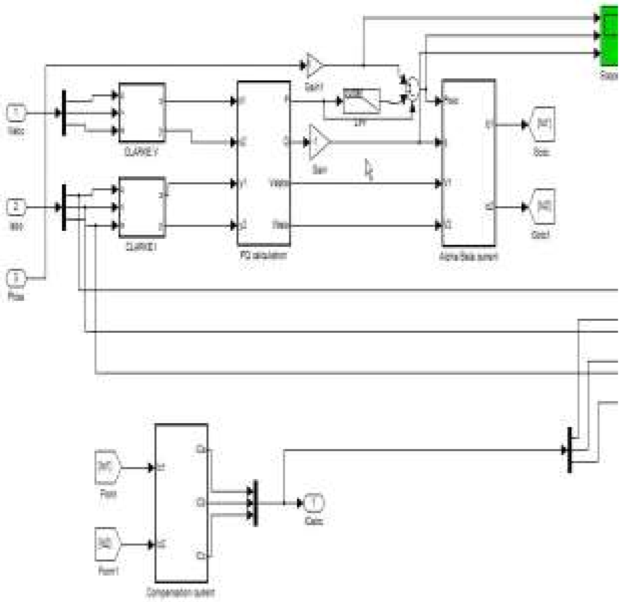
Figure 8: DVSI during load change

The dynamic performance of the AVSI is illustrated by displaying load currents, filter currents, source currents, and dc- link voltage. The load changes from unbalanced and nonlinear to balanced nonlinear load at an instant t_1. The AVSI begins to compensate the load instantaneously. The grid and filter currents settle within half a cycle. At the instant t_2 , the load changes back to its normal value. The source and filter currents again settle within a cycle. The rise and fall in dc-link voltage due to the sudden decrease and increase in load is not visible in the graph. This is because, the dc-link voltage control loop is slow and takes few cycles to settle down. Fig. 16 represents grid current transient during the change of operation of MVSI from grid injecting to grid sharing mode. It is considered that MVSI supplies 300 W during entire operation. A linear unbalanced load which takes an active power of 140 W is supplied by the DVSI until the time t_1 . Therefore, the remaining microgrid power of about 160 W is injected to grid. At the instant t_1 , the load changes to unbalanced and nonlinear which consumes an average power of 500 W. Therefore, beyond t_1 , an active power of 200 W is supplied from grid. This figure shows that unity power factor for grid current is achieved during grid injecting and grid sharing modes of operation.

SIMULATION CIRCUITS AND RESULTS:







CONCLUSION

A DVSI scheme is proposed for microgrid systems with enhanced power quality. Control algorithms are developed to generate reference currents for DVSI using ISCT. The proposed scheme has the capability to exchange power from distributed generators (DGs) and also to compensate the local unbalanced and nonlinear load. The performance of the proposed scheme has been validated through simulation and experimental stud- ies. As compared to a single inverter with multifunctional capabilities, a DVSI has many advantages such as, increased reliability, lower cost due to the reduction in filter size, and more utilization of inverter capacity to inject real power from DGs to microgrid. Moreover, the use of three-phase, three- wire topology for the main inverter reduces the dc-link voltage requirement. Thus, a DVSI scheme is a suitable interfacing option for microgrid supplying sensitive loads.

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