A NEW METHOD TO SHARE REACTIVE POWER IN MICROGRIDS

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Abstract - Microgrid is emerging as the answer to the high integration of local and distributed renewable generation to fulfil the rising demand for renewable electrical energy. The Microgrid approach implies some big challenges to be taken care. Among them, reactive power sharing by renewable resources is a challenge as in conventional grid the operator supported on a central control communication system manages it. This paper presents a new approach to handle the reactive power sharing in Microgrids. The sharing of reactive power in this new approach is with a distributive method based on measuring the local variables across the terminals of connection. This is made possible by adding a new functionality to the controller of the VSC interconnecting the renewable source to the Microgrid to take care of load needs and accordingly to configure the parameters of the controller changing the power sharing with high dynamics. The VSC modeling and design of its controller is done in dq reference frame. The reactive power control is vector one, decoupling the controlled variables. The work is carried out in PSIM software environment

Index Terms - Distribution Generation, Microgrid, Reactive power, Thevenin´s equivalent impedance, Voltage source inverter.

I. INTRODUCTION

Traditional approach of electrical power production has increased the production of carbon gas in the atmosphere in the last decade or so. The increase in the demand of electrical energy and the environmental problems with the traditional way of generation of electrical energy with fossil fuel have pushed the researchers and power producers to go for an alternate way. The alternate to the ongoing generation is to include as many renewable energy resources as possible. The problem with the inclusion of the renewable resources are that they are not available in bulk amount at one place as that of conventional generation. Rather they are scattered and in small amount at one point. To handle this new way of distributed generation, microgrid (MG) is emerging as an appropriate way for distribution system.

MG approach not only integrates the advantages of the distributed generation but also provide new technical ways for large application of grid-connected generation of renewable energy. MG is also emerging as a source of clean energy and resilient power source after the frequent natural. The resiliency of MG was proved in an earthquake in Japan in 2011 when the Sendai MG continued its supply after the earthquake[1][2]. Similarly, after the sandy storm of the USA in 2012, the research MG at the Princeton University continued its supply. According to the criteria of European Technology Platform (ETP), future electricity networks should be accessible, flexible, reliable and economic[3]. Along with the criteria's from ETP, it is also prime importance to use as many renewable resources as possible to face the environmental challenges caused by fossil fuel generation. All these circumstances lead to consider MG as the new energy supply system.

The recent development in power electronics is making it possible to integrate the distributed generation with renewable resources to the main system without many changes. If properly designed, the MG can not only use the advantages of distributed generation effectively but also provides a new technical way for the large-scale application of the grid-connected generation of renewable energy[4].Though there are many advantages with the renewable resources with MG technology still there are many challenges to be taken care of.Among many other issues in MG, the reactive power sharing is one of the main issue due to the high resistive lines in MG. The low voltage lines in MG have higher resistance than that of conventional lines that cannot be neglected as in the traditional medium voltage distribution lines. So the power flow with these lines becomes more complex as the line impedance contains both the resistive and inductive impedance.

The reactive power sharing and support used in most of the work in the MG are carried out using a central controller based communication system called as Microgrid Central Controller (MGCC)[2].A dedicated high bandwidth communication system is required, which puts extra cost on the system. It also includes slow control loops, which increase the response time

of the controller. Moreover, the dedicated hardware real-time communication system adds extra cost on the MG. The reliability of the system also decreases to a lower index due to the extra communication system. In fact, there are many research works going on to consolidate the MG technology. The work presented in this paper discusses a new distributive control method for reactive power sharing. The electronic device interconnecting renewable source is a VSC (Voltage Source Converter).The paper discusses a method for direct and dynamic contribution to the reactive power needs according to load demands. The modelling of the VSC is carried out in dq reference axis and the vector controller of the VSC is designed to react to the demand for reactive power with very high dynamics. The VSC observes the MG as its Thevenin´s equivalent impedance across its connecting terminal. When there is a change in load, the equivalent impedance across the VSC changes and the VSC contributes accordingly. The simulations are validated in PSIM software with mathematical derivations.

The remainder of the paper is structured as follows. First, in section II, details of existing power sharing methods and voltage control techniques are described. The voltage source converter and its control in dq reference frame is described in section III .Next, the analytical formulation of the MG is presented as thevenin´s equivalent impedance in section IV. In Section V, details of the proposed distributed reactive power control and sharing method is presented. Section V also demonstrates the performance of the proposed method and the paper concludes in Section VI.

II. POWER SHARING IN A MICROGRID

The expansion of the electrical power grid has also led the conventional power system to become more sensitive to cope with the reliability requirements and the diverse demand of power users [5]. The traditional power system with a central management system is not capable of coping with the challenges put forward by the incoming large-scale integration of different distributed generation which is increasing day by day [6]. To overcome this problem there is a need for management system to be located near to the consumer's point. With the advanced metering system added to the distribution system, the load can be made more responsive. MG combines distributed power, load, energy storage devices and control devices, forming a single and controllable power supply system [7]. Along with advantages comes some issues also and one of the issues to be look forward is the power sharing in a MG. Among power sharing, reactive power sharing is considered in this paper. The generally followed approach around the world is discussed in this section.

The voltage control and reactive power sharing is not a major problem in high voltage traditional network due to the capacitive compensation of both loads and transmission lines[8]. Moreover, the synchronous generators exhibit a self-stabilizing feature due to their high rotational inertia[9]. Therefore, the reactive power control has to be addressed with new approach in case of MG as both are not present in this domain. Since most of the generation units integrated in the microgrid are not of the synchronous generator type thus, MG needs to somehow mimic the droop characteristic existing in those synchronousgenerators to control the voltage and frequency. Taking this point in consideration, the frequency-active power and voltage- reactive power droop has been the main research work in many literatures of MG.

When there is a considerable amount of load decreases in MG or higher generation from DGs (Distributed Generation) then it is required to go for hard load curtailment which brings ON-OFF oscillations[10]. In the reference [10] the voltage droop which was originally developed for power sharing is used to soft curtailment to avoid the oscillations. The droop control is combined with PQ control to generate new references and control the MG in reference [11]. Weak droop control equations with a small power- dependent variation are used for generating the reference signal for PQ control after islanding has occurred. It is shown that the droop control along with PQ control can be used both for islanded and interconnected MGs. Three phase P/Q droop is used in [12] where the inverters are of unequal power ratings and the loads are nonlinear and unbalanced in nature.

The absence of synchronous generator in DG is tried to fulfil in many research by mimicking the behavior of the synchronous generator. In this way, governor and swing equations are virtually implemented on the VSI (Voltage source Inverter) to give it an inertial behavior. In [13] the comparison is made by developing small signal analysis between the virtual synchronous generator (VSG) and droop equations method applied in MG. These two methods are used to mimic the behavior of a synchronous generator in grid connected or islanded inverters. The use of inverters

mimicking the behavior of a synchronous generator is further studied as synchro converters in [14].

The drooping of the virtual flux is done instead of the inverter output voltage in [15]. At first, the mathematical relation between flux and power (active and reactive) is developed and then the droop slope between flux and power is used instead of the output voltage. [16] shows that adding derivative and integral gains to the conventional proportional droop function can increase the stability and dynamics of the power sharing. In [16] it is tried to use the droop slope without communication between DGs though the loops become slow to interact. The reactive power sharing is improved in [17]. The problem of power sharing due to line impedance is addressed in [17] by improving the conventional droop equation. A control strategy based on virtual resistance and phase locked loop is used in [18]. The drawbacks of conventional droop like the slow response is improved.

Similarly, in many research work the power sharing is done using the hierarchical control structure. In this approach, all the control of the MGs from the basic control of DGs to communications control with the MGCC has been classified into three categories. i) Level 0 control ii) Primary level control iii) Secondary level control and iv) Tertiary Control. In Level 0 control, the output of the DGs is controlled by taking the reference from the higher level. If the MG is interconnected with the grids, the DGs get the current reference and it gets the voltage reference if it is in islanded mode. The primary level control provides either the current reference or the voltage reference to the DGs by calculating it taking the required power flow as a reference. The secondary level of control uses certain algorithms to maintain the regulated voltage, frequency, and current if level 0 and primary level fails to maintain these values within the limit. Tertiary control is to maintain any special requirement if any of the MG like special power flow pattern, any special support to the grid is necessary.

A hierarchical control structure is presented [19] in which, firstly, smart MGs deal with local issues in a primary and secondary control. Secondly, these MGs are aggregated in a virtual power plant that enables the tertiary control. The dc control system is used for enhancing the economics and the resilient operation of a dc microgrid in [20]. The proposed hierarchical control strategy that applies to a dc microgrid improves the DC microgrid using V/I droop and MPPT [20]. A supplementary control loop is added in [21] to improve the stability of the system when using high angle droop in case of the weak system. The hierarchical control of three stages is proposed in [22]. The three hierarchical stages are 1) The primary control is based on the droop method, including an output-impedance virtual loop; 2) the secondary control allows the restoration of the deviations produced by the primary control, and 3) the tertiary control manages the power flow between the MG and the external electrical distribution system.Besides droop control and hierarchical level control other area where all the researchers have their attention is the virtual impedance. As the power sharing is different in MG due to the highly resistive lines so to compensate this the idea of virtual impedance is used. The main problem with the complex impedance is the coupling between active and reactive power, which makes the droop theory less applicable. To handle this problem in most of the research, work the virtual impedance is taken into consideration. [23] presents an approach with P/f and Q/V droop, while regulating the DG unit interfacing virtual impedance at fundamental and harmonic frequencies. The virtual resistance is modified (in [24]) in the droop controllers in accordance with the state in charge of each energy storage unit. The virtual resistance in [24] is adjusted to reduce the voltage deviation at the common dc bus. The investigation of the characteristics of the active and reactive power sharing in a parallel inverters system under different system impedance conditions is carried out in [25]. Instead of pure inductive or resistive loop intentional complex loop is considered in [25].

The resistive nature of low voltage lines in MG is neutralized by connecting virtual inductance at the interfacing inverter output in [26]. It is shown that the virtual inductance can effectively prevent the coupling between the real and reactive powers by introducing a predominantly inductive impedance even in a low-voltage network with resistive line impedances. A transform matrix where only the knowledge of ratio of resistance and inductance of the lines are used to modify the power sharing in [3]. Each inverter supplies a current that is the result of the voltage difference between a reference ac voltage source and the grid voltage across a virtual complex impedance.
Although many works are being carried out still, there are many challenges to be addressed in MGs. The complex impedance of MG line in comparison to the inductive line of traditional power system still is a problem in estimating the power sharing. The voltage loops used are not fast enough in responding, as it is

desired. There are many complicated control structures applied in many works. The absence of inertia in DGs has not been solved yet now though a partial solution is done by mimicking the behavior of the synchronous generator. The reactive power sharing is also still a problem as the complex impedance of the MG lines does not allow using the traditional approach of power flow. Among these, the reactive power problem is addressed with a new distributive approach in this paper.

III. VSC AND ITS CONTROLLER

The VSC along with a well-designed controller is used in this work to contribute the reactive power to the MG. The VSC is the electronic interface, which is used to connect the DG to the MG. A voltage source converter is a bidirectional converter, which can convert the power from DC to AC and vice versa as well as control the active and reactive power independently [27]. Furthermore, if properly controlled, the VSC can set the reactive power as inductive, capacitive or null independent of the active power [27]. In a Microgrid, the voltage is not a global variable like frequency. Therefore, the voltage can change with the change in the load in terms of both location and magnitude. Hence, by controlling the reactive power locally, the voltage is also be controlled.

The distributed reactive power contribution with fast dynamics from the VSC is possible by designing a controller in dq axis. The reference to contribute in the reactive power is generated using the Thevenin´s equivalent impedance (ETI) in the controller circuit. Figure 1. shows the dq axis reference frame electrical circuit of the VSC. The equations of the VSC in dq reference frame is presented in equation (1).

$$\left.\begin{aligned} V_d &= e_d - Ri_d - \Delta V_d + \omega_e L i_q \\ V_q &= e_q - Ri_q - \Delta V_q - \omega_e L i_d \end{aligned}\right\} \quad (1)$$

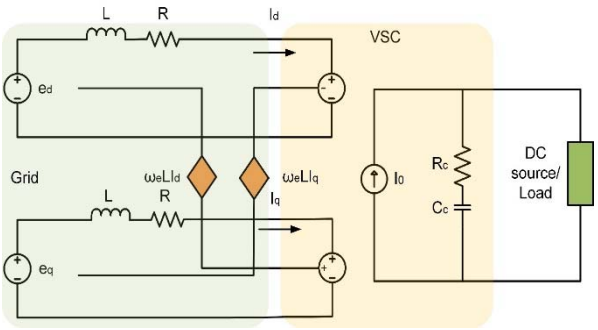


Fig. 1. Modelling of VSC in DQ reference frame

Equation (1) shows that the i_q and i_d component of the current are responsible for generating the V_d and V_q voltages which finally is responsible for generating the signals used for switching the VSC. The i_q and i_d component also have cross coupling component as i_q component is seen in the equation of V_d and $i_d$component in the equation of the V_q.

In the circuit shown in Figure 1 the VSC is analyzed as a power transfer device that converts AC active power into DC power and vice-versa. If the AC active power is transferred to DC side, it works as a rectifier and the voltage level of the DC side increase. Similarly, if the active power is transferred from the DC side to the AC side the voltage level of the DC source decreases and the VSC acts as an inverter. The reactive power is exchanged between the AC side of the VSC and the grid.

The equations (1) are furrther analyzed in Laplace domain as shown in equation (2).

$$\left.\begin{aligned} e_d &= (R + sL)i_d - \omega_e L i_q + v_d \\ e_q &= (R + sL)i_q - \omega_e L i_d + v_q \end{aligned}\right\} \quad (2)$$

Similarly, the equations developed for the DC side are shown in equation (3).

$$V_{DC} = \frac{1}{A}\left(\frac{\frac{3}{2}(V_d i_d + V_q i_q)}{V_{DC}} + \left(\frac{C}{sR_c C + 1} + \frac{C_1}{sR_1 C_1 + 1} \right) V_0 \right) \quad (3)$$

The power been exchanged from ac to dc side is $3/2(V_d\ i_d + V_q i_q)$ which is an integral part of the equation (3). The control circuit for the VSC is developed using the above equations. The VSC is used as a medium to connect the renewable resources to the microgrid. The VSC supplies the active and reactive power to the grid according to the requirement of the grid. If renewable resources are connected to the grid through these VSC then they can act as a source to support power to the MG according to the requirement.

A well-designed current controller has to produce the currents, which exactly follows the current reference. In this way, the power can be controlled and supplied according to the requirement. The current controller for the VSC is designed in which the currents i_d and i_q follows its references I_d^* and I_q^* respectively. So the main objective of the controller is to make the line currents i_d and i_q to follow the references I_d^* and I_q^* respectively. While working in the dq reference frame it is needed to deal with the cross coupling terms so that if we want to make a change in one quantity the other quantity has to be counteracted in order to guarantee a high dynamic performance.

A decoupled PI(Proportional Integrator) type controller is used to get high performance current controller.

The equations (1) and (4) are used to design the controller of the VSC.

$$\begin{cases} \Delta V_d = k_p(I_d^* - I_d) + k_i \int (I_d^* - I_d)dt \\ \Delta V_q = k_p(I_q^* - I_q) + k_i \int (I_q^* - I_q)dt \end{cases} \quad (4)$$

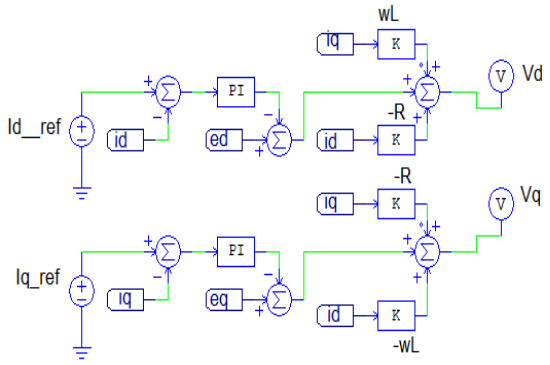


Fig. 2 Controller Designed in PSIM

Figure 2. Shows Id_ref is the current reference taken for the active power flow and Iq_ref is the current reference for the reactive power flow. Using the PI controller and the decoupling circuit exact amount of power is made to flow independently according to the requirement. The output of the controller Vd and Vq are fed to the switching circuit of the VSC by converting in abc form. The dq component is converted into abc component using transformation block of PSIM.

IV. ANALYTICAL FORMULATION OF EQUIVALENT IMPEDANCE OF THE GRID

The model developed in section three is used to contribute reactive power to the MG using VSC. Figure 3 shows the block diagram of the grid and VSC connected. The VSC is connected at a distance from the load point. Similarly, the grid is also at a certain distance from the load. The resistance and inductance of the lines are considered for low voltage distribution line. The circuit diagram of the VSC connected to the MG is shown in Figure 4. The circuit diagram is used to develop the analytical formulation of the equivalent Thevenin`s impedance as observed by the VSC across its terminals. Vg is the voltage of the MG and VSC is the voltage of the VSC. I1 is the current flowing from the VSC and Ig is the current flowing from the grid. Z1 is the line impedance in the VSC side and Zg is the line impedance in the MG side. Z_L is the load impedance at an instant of loading. VL is the voltage level at the load-connected point.

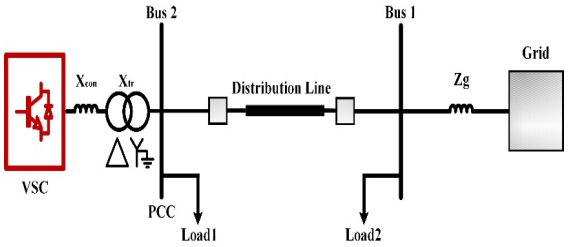


Fig. 3. VSC connected with the Microgrid

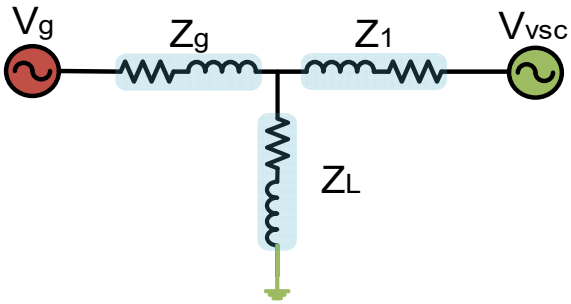


Fig. 4. Equivalent Impedance observed by VSC

The equivalent Thevenin's impedance observed by the VSC is mathematically derived whose final expression is shown in equation (5) and (6).

$$R_{VL} = \frac{R_L(I_1^2 + I_1 I_G(\cos(\Phi_1 - \Phi_G) - X_L(I_1 I_G(\sin(\Phi_G - \Phi_1))}{I_1^2} \quad (5)$$

$$X_{VL} = \frac{R_L(I_1 I_G(\sin(\Phi_G - \Phi_1) + X_L(I_1^2 + I_1 I_G(\cos(\Phi_1 - \Phi_G)}{I_1^2} \quad (6)$$

The equations (5) and (6) shows the equivalent resistance and the reactance observed by the VSC across its connected terminals at any instant. Based on the model designed in section III and the analytical derivation of section IV the VSC is made to react to the load changes and contribute the MG the necessary reactive power it can support. The next section describes the response of the VSC to the change of load.

V. CONTRIBUTION FROM THE VSC

The VSC is connected to the MG as shown in Figure3. The load is changed in steps and accordingly the equivalent impedance across the VSC terminal also changes as shown in equation (5) and (6). This change is sensed by the VSC in terms of dynamic change in the waveform of reactive power. After sensing according to equivalent thevenin´s impedance and finally the Iqfill reference which is shown in Figure 7, it generates the Iq_comp. A functional block is added to the controller to generate the compensation to be provided by the VSC. The functional block consist of a c-block which is used to sense the change in load and generate the compensation as a Iqcomp. As shown in the figure it operates in certain intervals according to

the clock. The inputs to the C-block are the change in reactive power. The flowchart for the C-block is presented in Figure 6.

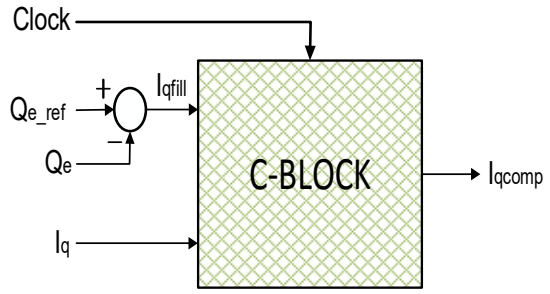


Fig. 5. External digital block to generate the reference for the controller

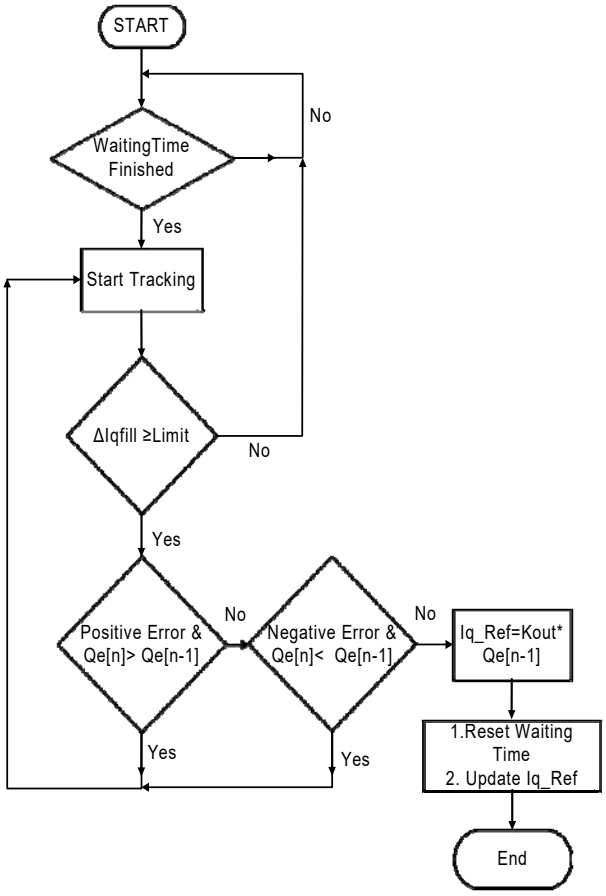


Fig. 6. Flowchart of the program used in the C-Block

The algorithm shows that after certain waiting time the change in reactive power is measured and if it is beyond the limit the new Iq compensation is generated and fed to the controller of the VSC. Similarly, the nature of the change is also identified if the demand of the reactive power is increased or decreased.

This reference is fed to the controller of the VSC and accordingly the Iq component is changed which finally changes the reactive power contribution. Figure 7 shows the change in the Iqfill component according to the load change. According to the change in Iqfill the reference generated by the controller is Iq_comp. Using this Iq_comp the real iq generated by the VSC also changes.

The VSC is connected to the MG as shown in Figure3. The load is changed in steps and accordingly the equivalent impedance across the VSC terminal also changes as shown in equation (5) and (6). This change is sensed by the VSC in terms of dynamic change in the waveform of reactive power. After sensing according to equivalent thevenin´s impedance and finally the Iqfill reference, it generates the Iq_comp reference which is shown in Figure 8. This reference is fed to the controller of the VSC and accordingly the Iq component is changed and accordingly the reactive power contribution is changed. Figure 7shows the change in the Iqfill component according to the load change. According to the change in Iqfill the reference generated by the controller is Iq_comp. Using this Iq_comp the real iq generated by the VSC controller is shown in Figure 8. There are two peaks shown in the i_q graph in Fig. 8. The transient shown in black circle is the initial change shown during the load change at 0.1s and 0.15s. The actual response from the controller is shown by red circle, which is due to the I_q_comp. This change in I_q makes the VSC to contribute the MG with high dynamics as shown in Fig. 8 as Qe. Inverted black arrows show the contribution. The load is changed in two steps and the VSC contributes the MG instantly in both the cases.

Fig. 9 shows three plots in one diagram where Q_L is the change in load at 0.1s and 0.15s. Accordingly the contribution from the MG and the VSC is there at 0.1s and 0.15s.Fig. 9 shows that the contribution from the VSC is instantly provided. Similarly, Fig. 10 shows the change in equivalent reactance X_vL with the change in load. The X_vL as derived in section IV is the thevenin´s equivalent reactance across the terminal of the VSC. It can be observed the change in the load is reflected as the change in equivalent reactance across the terminal of the VSC. Fig. 11 shows the X_vL and reference for reactive power iq. It can be observed that as the X_vL changes the reference from the controller Iqcomp. in blue color is also changed which is followed by the iq of the controller which finally produces the reactive power to be contributed to the MG. The change in load is reflected at the terminals of the VSC which solves the issue of measuring across the load terminal. So only measuring the variables across its point of connection the VSC can react instantly and give necessary contribution of reactive power according to its capacity.

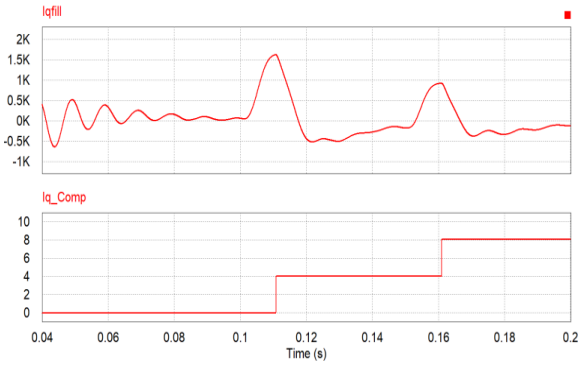


Fig. 7. Generation of Iq reference based

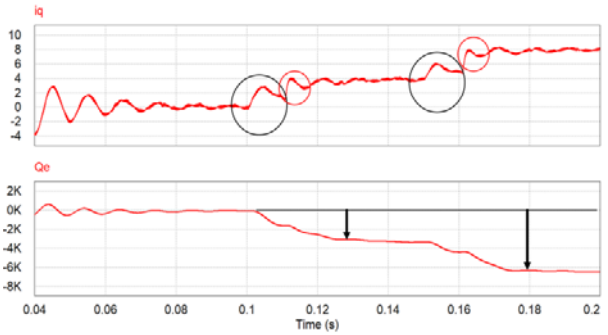


Fig. 8. Reactive power support from the VSC

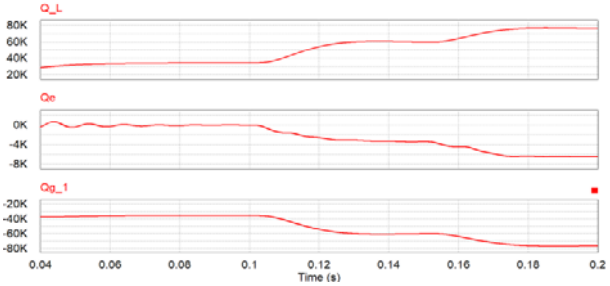


Fig. 9. Load supplied by the MG and VSC

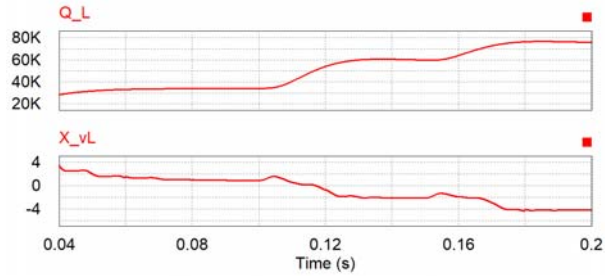


Fig. 10. Change in equivalent reactance with the change in load

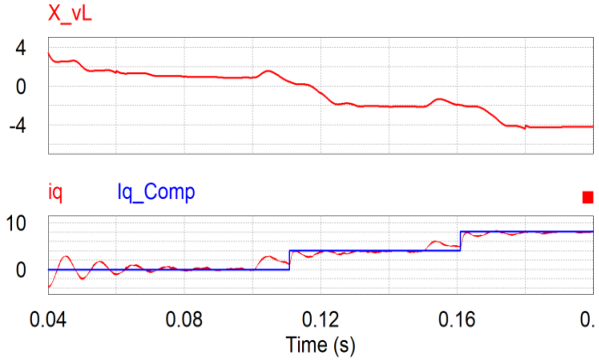


Fig. 11. Reference generation with the change in equivalent reactance

CONCLUSION

The result of this paper shows that the reactive power is contributed by the VSC when there is load change. The contribution was done with high dynamics. The VSC acted by only measuring the local variables across its point of connection. It is shown that with the proper design and modelling of the VSC and its controller the contribution was made possible. In this way, the reactive power support was made possible without the central communication approach. If all the VSC in the MG can support the grid like this approach by measuring the local variables, then the necessity of the central communication system can be limited to few DGs. The percentage of sharing of the reactive power can be changed according to the capacity of the particular renewable resource.

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