Parallel Operation of Voltage Source Inverter with Hydro based Synchronous Generator

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Abstract: This paper describes a control approach applied to the voltage source inverter (VSI) connected with synchronous generator (SG) equipped with exciter and governor based hydraulic turbine to supply power to isolated load. VSI is suitable for the connection of solar PV, wind power or other distributed generator as per availability. SG is operated as a voltage and frequency control mode. Frequency and voltage of the output bus is controlled by SG itself using aggregated load frequency control by governor and excitation control respectively. Synchronization of the inverter with the SG is achieved through Phase Locked Loop (PLL). The d-q based control strategy is deployed in the inverter so that it is operated in line with the output bus of the SG. Inverter is design to extract all the available active power to the load, shares the requisite reactive power with SG using droop control mode whereas SG is operated to provide the deficit active power to the load and shares the requisite reactive power with inverter using droop control mode. The effectiveness of the control techniques of this system is demonstrated through MATLAB Simulink simulation under constant as well as varying load condition.

Keywords: Synchronous Generator, Voltage source inverter, Hydraulic Turbine and Governor System, Excitation System, d-q Modelling

1. Introduction

Renewable energy sources have attracted attention worldwide due to soaring prices of fossil fuels. The increase in renewable Distributed Generation (DG) penetration and presence of multiple DG units in proximity has brought about the concept of micro grid; such composite system can operate in autonomous modes. Many DG technologies that exist today have pros and cons of their application [1]. Among these sources wind and solar can be complementary to each other in time, therefore wind and PV hybrid power system could make full use of clean energy and have high reliability [2]. But, in the scenario like Nepal, there are huge availability of small hydro power along with other renewables such as wind or solar energy. Thus there is necessity of suitable control strategies for parallel operation of these sources and have ability to complement each other. For the connection of renewables such as wind or solar energy, suitable power electronics converter is required. VSI is suitable for the connection of these renewables to the grid. The control of parallel connected VSI has two instantaneous average values control loops: one for voltage and another for current. The first one controls the output voltage of the inverter while the second is designed to control the parallel operation of the inverters [3]. To provide electric power of high reliability, the converters in the microgrid often rely on autonomous droop control methods to reduce their dependence on communication both in the islanded mode and the grid-connected mode [4] &[5]. As the number of DG applications with power electronic interfaces in the grid increases, it is becoming unacceptable to disconnect the generating units while every time disturbances occur and guaranteeing the actual standards of the converter connected to the grid [6]. The control topology for bi-directional voltage source converter for composite wind-solar-hydro power system is such that any of the energy conversion system (ECS) or in combination can work in utility synchronized or autonomous modes to meet the demand [7]. It is required to compare the synchronization techniques for converter-interfaced DG systems in terms of their capability in tracking the grid frequency variations in the presence of low order harmonics and unbalance conditions [8].

From the literature it can be comprehended that utility synchronization strategy to extract maximum available power for inverter interfaced remote DG system along with its parallel operation is a potential area of research for accomplishing unremitting power supply to the remote loads.

The potential for small hydroelectric systems depends on the availability of suitable water flow and head, where the resource exists, it can provide cheap clean reliable electricity. Hydroelectric plants convert the kinetic energy of a waterfall into electric energy. The power available in a flow of water depends on the vertical distance the water falls (i.e. head) and the volume of flow of water in unit time. When SG is used for small or micro hydro applications, load active/reactive power requirement is meeting by SG itself. So for the integration of VSI to this hydro system, the control objective are deployed in the inverter so that it is operated in line with the output bus of the SG. Ideally the system controller is expected to have the following requirements:

- Synchronization of the inverter with the through Phase Locked Loop (PLL).
- SG is operated to provide the deficit active power to the load and shares the requisite reactive power for the load with Inverter using droop control mode.
- VSI is operated to extract all the available active power to the load whereas shares the requisite reactive power for the load with SG using droop control mode.

In the case of stand-alone or autonomous systems, the issues of voltage and frequency control (VFC) are very important. For the synchronization of the inverter to the SG, the inverter voltage magnitude, frequency and phase are adjusted to be in synchronization with SG voltage. This is achieved through phase locked loop (PLL) and the synchronization controller. Once the synchronization is done, the inverter is connected to the common bus providing d-q based current control to extract all the available active power to the load whereas shares the requisite reactive power with SG using droop control mode.

This hybrid system is used to supply the unremitting power to remote isolated loads where the resources exist but unavailability of national grid. Thus this system is suitable for the country like Nepal where there is abundant availability of the small hydro, and used of the VSI interfaced distributed generation like solar, wind as complement to this as per availability to meet the load demand.

2. Configuration of Composed Composite System

The schematic depicting VSI-SG composite system with controller is shown in figure (1). The proposed system consists of hydro turbine driven SG equipped with exciter and hydraulic governor in parallel with inverter. The SG and VSI are connected on common bus known as point of common coupling (PCC). A load or combination of load is connected at PCC. LR Filter is connected at the output terminal of the VSI, which would enable interface of VSI to the loads and SG. A step changing current source connected to dc link equipped with capacitor storage system. This voltage source inverter is suitable for the connection of solar PV, wind power or other distributed generator as per availability. Also this hybrid scheme is structured to enable power flow to load from a VSI or any combination of VSI and SG.

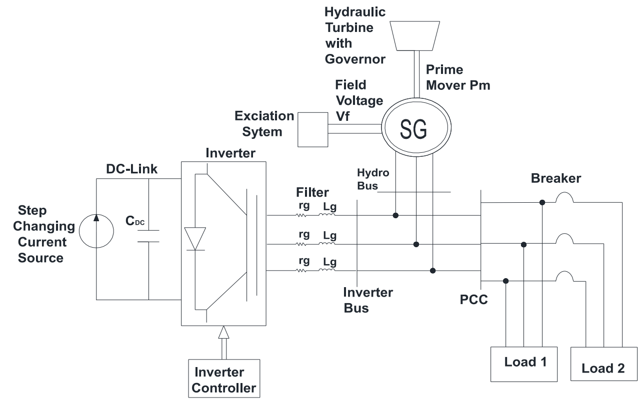

Figure 1: Configuration of proposed System

3. Modeling of Hydro System

An adopted model of SG with excitation system and hydro turbine with governor system for load frequency as well as voltage control are presented below.

3.1 Modeling of Synchronous Generator

This section describes a generalized model of synchronous generator. Generally, the model of SG is composed of a swing equation to govern the motion of rotor and voltage equation to determine terminal voltage and phase current. To simply the model SG is assumed with one pairs of poles regardless of physical damping windings.

3.1.1 Swing Equation of SG

Swing equation defines the relation between the deviation of rotor speed and the imbalance of the torque. The swing equation of the SG is given by (1):

$$T_m - T_e = \frac{P_m - Pe}{\omega} = J\frac{d\Delta\omega}{dt} + D\Delta\omega \qquad (1)$$

Here, T_m and T_e are the mechanical torque and electromagnetic torque, J is the moment of inertia, D is the damping coefficient, ω is the rotating speed of rotor which equals the electrical angular velocity in the assumption of one pair of pole.

In the small excursion of the angular speed ω can be substituted by the reference angular velocity ω_0 of the grid. Therefore a simplified swing equation is given by (2):

$$P_m - P_e = J\,\omega_0\frac{d\Delta\omega}{dt} + D\,\omega_0\,\Delta\omega \qquad (2)$$

3.1.2 Voltage Equations of SG

The effect of Park's transformation is to transform all the stator quantities from phase abc into a frame reference rotating with rotor i.e. d-q rotating reference frame. The main aim of the d-q model is to eliminate the dependence of inductances on rotor position. The d-q model should express both stator and rotor equations in rotor coordinates, aligned to rotor d and q axes because, at least in the absence of magnetic saturation, there is no coupling between the two axes. The transformation from abc phase variables to the dq0 variables can be written in the following matrix form:

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3)$$

Thus SG can be viewed as a DC generator where main field winding flux is along d-axis and EMF is primarily along the rotor q-axis.

The stator flux linkage can be written as

$$\Psi_d = -L_d\, i_d + M_{af}\, i_f \quad (4)$$

$$\Psi_q = -L_q\, i_q \quad (5)$$

Where Ψ_d, Ψ_q are the flux linkage in the d and q-axis, L_d, L_q are the self-inductance in the d and q axis, M_{af} is the mutual inductance between armature and field winding and i_f is the field circuits current. The terminal voltage e_d and e_q can be obtained from

$$e_d = p\Psi_d - \Psi_q\, \omega - R_a\, i_d \quad (6)$$

$$e_q = p\Psi_q + \Psi_d\, \omega - R_a\, i_q \quad (7)$$

Combining (4), (5), (6) and (7) and ignoring the transients terms $p\Psi_d$ and $p\Psi_q$, the terminal voltage can be written as,

$$e_d = -L_d \frac{di_d}{dt} + X_q i_q - R_a i_d \quad (8)$$

$$e_q = E_q - L_q \frac{diq}{dt} - X_d i_d - R_a i_q \quad (9)$$

Where, X_d, X_q are the reactance in the d and q-axis and E_q is the back EMF due to rotor movement given by the following equation.

$$X_d = \omega\, L_d\,;\ X_d = \omega\, L_q;\ E_q = M_{af}\, i_f\, \omega \quad (10)$$

3.2 Modelling of Hydro Turbine with governor

Power system performance is acted by dynamic characteristics of hydraulic governor-turbines during and following any disturbance, such as occurrence of a fault, loss of a transmission line or a rapid change of load. Accurate modelling of hydraulic governor-turbines is essential to characterize and diagnose the system response during an emergency. The basic function of a governor is to control speed as per load variations. The general principle of load/frequency control involves feeding back speed error to control the gate position. In order to ensure satisfactory and stable operation of multiple units speed governor is provided with droop characteristics. Here we consider electro-hydraulic governors with three terms controller namely proportional-integral-derivative as shown in the figure (2) below. These allow the possibility of the higher response speeds by providing both transient gain reduction and transient gain increases. Proportional-integral-derivative gains may be selected to result in the desired temporary droop and reset time.

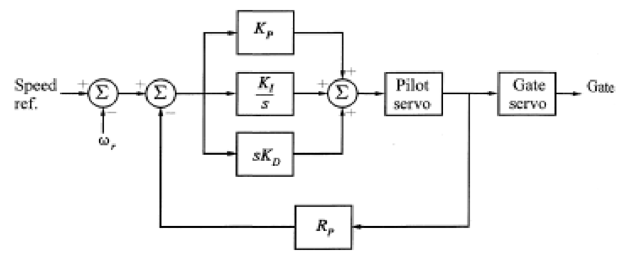

Figure 2: PID Governor

The primary source for the electrical power provided by utilities is the kinetic energy of water which is converted into mechanical energy by the prime movers. The electrical energy to be supplied to the end users is then transformed from mechanical energy by the SG. The speed governing system adjusts the generator speed based on the input signals of the deviations of both system frequency and interchanged power with respect to the reference settings. This is to ensure that the generator operates at or near nominal speed at all times. The hydraulic unit characteristic of a single penstock is:

$$\frac{dq}{dt} = a_g \frac{A}{L}\,(h_0 - h - h_l) \quad (11)$$

$$q = AU \quad (12)$$

Where q is turbine flow, h_o is initial steady-state head, h is hydraulic head at gate, h_l is head losses due to friction in the conduit, a_g is gravity acceleration, A is penstock cross section area, L is conduit length, U is water velocity, g is real gate opening and G is ideal gate opening based on the change from the no load to full load being equal to 1 per unit.

The terms for the physical design of the plant describe the water starting time constant with normalized terms using the per unit system as:

$$\frac{dU}{dt} = \frac{h - h_t}{T_W} \quad (13)$$

Where, T_w is the water starting time at rated load

The turbine representation is based on steady state measurements related to output power and water flow. The output power is:

$P_m = (U - U_{NL})\, h$ (14)

The above equation is based on the ideal gate opening based on change from no load to full load being equal to 1 pu. The ideal gate opening is related to real gate opening as follows

$G = A_t\, g$ (15)

Where, A_t is the turbine gain given by

$A_t = \frac{1}{(g_{FL} - g_{NL})}$ (16)

3.3 Excitation System Model

DC excitation systems without the exciter's saturation is shown in figure (3) below. This model represents a field -controlled alternator excitation system with non-controlled rectifiers applicable to the brushless excitation system. The basic elements of the excitation system is voltage regulator and exciter.

The voltage regulator output V_R, is used to control the exciter voltage E_{FD}, The exciter is represented by the following transfer function between the exciter voltage E_{FD} and the regulator's output V_R.

$\frac{V_R}{E_{FD}} = \frac{1}{K_E + sT_e}$ (17)

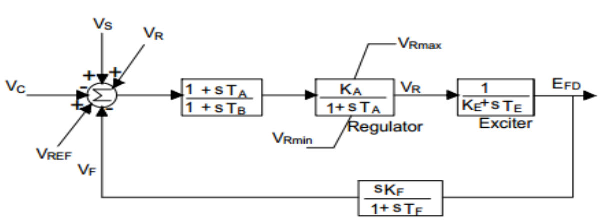

Figure 3: Excitation System

A signal derived from field voltage is normally used to provide excitation system stabilization via. rate of feedback with gain K_F and time constant T_F .

4. Modelling of Inverter

The selection of the controllers for the inverter is based on the requirements and characteristics of the connected voltage source and of the synchronous generator. The frequency limits and continuity of service are regulated by the controller. The VSI must be capable of operating as the unique power source or in conjunction with a SG.

The inverter control strategy is based on current control mode. Inverter is operated in line with the output bus of the synchronous generator. It is design to extract all the available active power to the load whereas shares the requisite reactive power for the load with Synchronous Generator (SG) using droop control mode.

4.1 Transformation of the measured voltage and current at PCC from stationary to rotating frame

Using reference frame transformation, measured current signals at the PCC are transformed from abc to dq_0 rotating frame. Any arbitrary rotating frame can be chosen as reference frame. In the chosen reference rotating frame the d-axis component represents active power, while the q-axis component represents reactive power.

Transformation is made in two steps:

First a transformation from the three phase stationary coordinate to the two phase so called αβ stationary coordinate system is done by the following equation:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (18)$$

The transformation from to the rotating dq_0 frame is achieved by the means of the following equation:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ -\sin\omega t & \cos\omega t \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (19)$$

Where, ω is the synchronous angular frequency of the system. The DC components in the rotating dq0 frame i_d and i_q corresponds to the positive sequence fundamental components of i_α and i_β. Since dq transformation is the one that converts frequency dependent signals in to ones with constant value, a three phase current values yields constant i_d and i_q. The relation between the dq and active and reactive components depends on the selected frame reference. To suppress noise and avoid transients in the measured currents signals in dq frame, they have to be low pass filtered.

5. Control Strategy

5.1 Inverter Controller

5.1.1 Inverter Synchronization to the PCC

Synchronization of the voltage source inverter with the synchronous generator voltage and frequency is achieved through PLL system. A PLL system is implemented in the synchronous reference frame as shown in the figure (4).

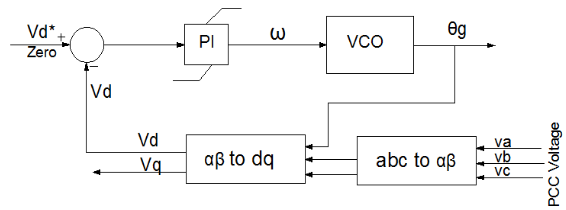

Figure 4: Structure of the PLL system implemented in dq reference frame

This type of PLL is able to provide the PCC frequency information. The output phase provided by the PLL will be used as input to the PI controller in order to have adaptive tuning in respect to the SG frequency. PLL controller plays an important role in this situation. The regulator should be designed to respond with minimum of overshoot to the frequency and voltage variation. When the difference between PCC phase angle θ and inverter phase angle θ_{inv} is reduced to zero ($\Delta\theta=0$), the PLL become active and lock is realized by setting the reference of the d-axis voltage to zero, following that

$$V_d=0;\ V_q=\sqrt{3}\,V_{phase} \qquad (20)$$

The PLL PI controller parameters are the trade- off between a fast dynamics system providing quick synchronization and slow system providing filtered output. The PI loop filter controls the oscillation frequency of the voltage controlled oscillator (VCO) with the sum of voltage proportional to the error signal and a voltage proportional to the time integral of the error signal. Therefore under ideal conditions this PLL structure performs satisfactory.

5.1.2 Regulation of Active Power and droop control of Reactive Power

The VSI control scheme shall consists of two cascaded control loops. The inner current control loops regulate independently the d-axis and q-axis VSI ac-side current components, i_{dg} and i_{qg}, in the synchronously rotating reference frame utilizing PLL scheme. The outer control loops regulate the dc-link voltage and the reactive power exchanged between the VSI and the PCC. The ac-side circuit equations of the VSI can be written as

$$\frac{d}{dt}\,i_{gabc} = \frac{r_g}{L_g}\,i_{gabc} + \frac{1}{Lg}\,(v_{gabc} - v_{sabc}) \qquad (21)$$

Where, r_g and L_g be the coupling resistance and inductance, i_{gabc} and v_{gabc} be the instantaneous inverter grid side current and voltage and v_{sabc} be the system grid voltage respectively. Applying the synchronously rotating reference frame transformation with the d-axis aligned to the grid voltage vector v_s ($v_s=v_{ds}$, $v_{qs}=0$), the following d-q vector representation can be obtained for modelling the controller ac-side.

$$v_{dg}=r_g i_{dg} + L_g\, d\frac{i_{dg}}{dt} - \omega_s L_g i_{qg} + v_s \qquad (22)$$

$$v_{qg}=r_g i_{qg} + L_g\, d\frac{i_{dg}}{dt} - \omega_s L_g i_{dg} \qquad (23)$$

Where, v_{dg}, v_{qg} and i_{dg}, i_{qg} are d and q component of the inverter grid side voltage and current respectively. v_{dg} and v_{qg} can be obtained by the following feedback loops and PI controllers.

$$v_{dg}= \left(k_{pg} + \frac{k_{ig}}{s}\right)(i^*_{dg}-i_{dg}) - \omega_s L_g i_{qg} + v_s \qquad (24)$$

$$v_{qg}= \left(k_{pg} + \frac{k_{ig}}{s}\right)(i^*_{qg}-i_{qg}) - \omega_s L_g i_d \qquad (25)$$

The reference i^*_{dg} and i^*_{qg} are obtained from the outer loop control.

The dc link voltage control generates the reference for d-axis components. Which ultimately control the active power transfer to the PCC.

$$i^*_{dg} = \left(k_p + \frac{k_i}{s}\right)(V^*_{dc} - V_{dc}) \qquad (26)$$

The reactive power control is done by droop sharing with SG by suitable droop factor which generates the reference for q-axis components.

$$i^*_{qg} = \left(k_p + \frac{k_i}{s}\right)(Q^*_g - Q_g) \qquad (27)$$

Where $Q_g = -\frac{3}{2} v_{ds} i_{qg} = -\frac{3}{2} v_s i_{qg} \qquad (28)$

The overall control block diagram are shown in figure (5) below.

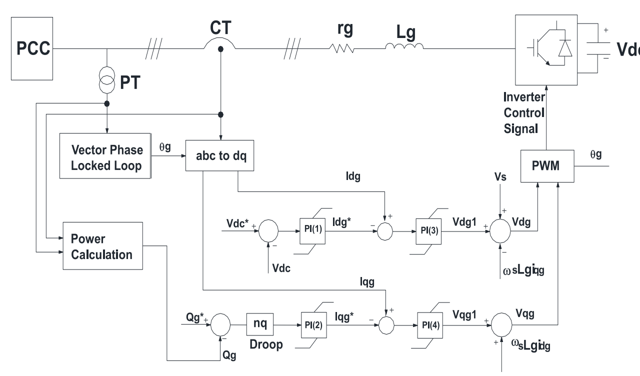

Figure 5: Overall control structure of inverter

This scheme VSIs output active power is proportional with d-component of the current, where the reference d-component of the current is obtained by comparing the dc link voltage with reference voltage followed by PI controller. In the same instant it relate VSIs output reactive power is proportional with q-component of the current, where the reference q-component of the current is obtained by reactive power droop in line with synchronous generator followed by the PI controller. Thus this VSI can operate in line with the output bus of the synchronous generator and it extract all the available active power to the load whereas shares the requisite reactive power for the load with SG using droop control mode.

5.2 SG Controller

5.2.1 Frequency Drooping and Regulation of Real Power

For SG, the rotor speeds maintained by the prime mover and it share load evenly (inspirational to their nominal load). To vary the real power delivered to the grid according to the grid frequency which is a control loop called "frequency droop". When real power demand increases, the speed of SG drops due to increased T_e in (1). The power regulation system of the prime mover increases mechanical power so that new power balance is achieved. Typical values for the frequency droop are a 100 % increase in power for the frequency decrease between 3% to 5% (from nominal values).Thus as described in above section load frequency control of SG is achieved by hydro turbine with governor. The controller is designed so that it maintains the constant frequency in the PCC by comparing the reference frequency with measured one followed by the governor action and also it provides deficit active power to the load.

5.2.2 Regulation Reactive Power

As described above the SG is equipped with excitation control. The excitation control is used to maintain the constant fixed voltage at the PCC. Thus for the regulation of the voltage at PCC, reactive power flowing out of the SG can be realized. Thus for the share of the reactive power to the VSI, V_{ref} for the excitation control can be obtained from the droop control mode as shown in the figure (6) below.

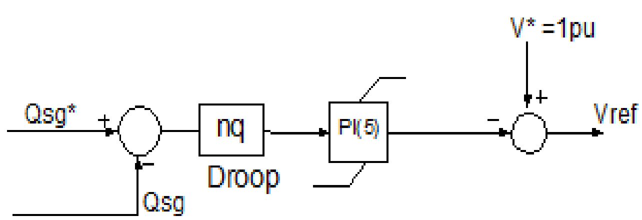

Figure 6: Reactive Power Drop of SG

6. Simulation Results

To verify this proposed control strategy, a MATLAB/SIMULINK-based simulation has been built. The parameters of the inverter and hydro system used in the simulation are given in the table I and table II respectively.

Table I: Parameters of VSI

Parameters	Values	Parameter	Values
Rated Power	40 kW	Nominal Voltage (line-line)	400 V
DC-Link Voltage	680 V	Reactive Droop	3%
DC-Link Capacitance	1800×10^{-6} µF	r_g	0.048 Ω
Nominal Frequency	50 Hz	L_g	2 mH

Table II: Parameters of Hydro System

Synchronous Generator			
Parameters	Values	Parameter	Values
Rated Power	125 KVA	Nominal Voltage	400 V
Nominal Frequency	50 HZ	Pole Pair	2
Stator Quantities (pu)	R_s=0.02594, L_l=0.09, L_{md}=2.75, L_{mq}=2.35		
Field Quantities (pu)	R_f=0.00778, L_{lfd}=0.3197		
Hydraulic Turbine & Governor			
Servomotor	K_a= 5, T_a=0.05 sec		
Regulator	R_p=0.03, K_p=3.5,K_i=0.54, K_d-0.105, t_d=0.1		
Gate Opening Limit (pu)	g_{min}=0.01, g_{max}=0.97518		
Reactive Droop	3 %		
Exciter			
Regulator	K_a=300, T_a=0.01 sec		

A test system as shown in figure (1) is chosen whose parameter are as per given above Table I and II. In the inverter simulation a step changing current is feed to the DC link across the capacitor. This system is supplying a load with active power demand equal to 110 kW and reactive power demand equal to 10 kVAR. After 2.5 sec an additional load with active power demand equal to 5 kW and reactive power demand to 5 kVAR is added to the system. The waveform of dc bus voltage and the input current fed to the DC link of the inverter is shown in the figure (7) below. In the DC Link voltage waveform some initial transient can be seen which cause the dc bus voltage rise to 725 V, subsequently PI controller regulate the dc bus voltage. At 2.5 sec when additional load is connected, there is sudden transient in DC link voltage. The DC link voltage is maintained at fixed defined value ie. 680 V.

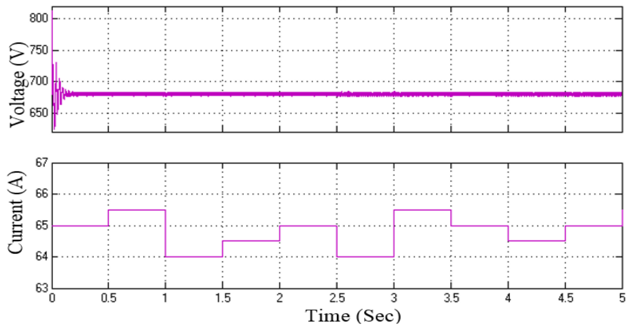

Figure 7: DC Link voltage and inverter input current waveform

The active power generated by the hydro based SG, Inverter and total active power supplied to the load are shown in the figure (8). In this figure, we can see that inverter has supplied all the available active power i.e. its rated power (40 kW) to the load, whereas synchronous generator is operate to provide the deficit active power to the load. At 2.5 sec, a load of active power demand of 5 kW is added to the system. As inverter already supplied its rated power to the load its output do not changes whereas the increased demand is meet by the SG itself.

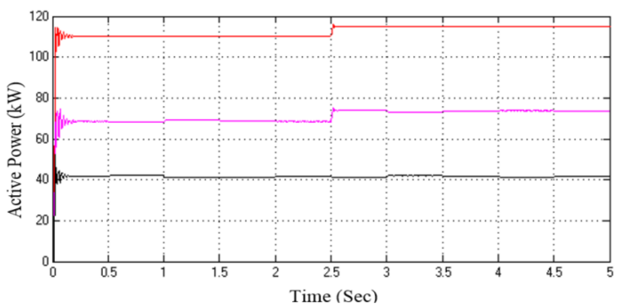

Figure 8: Active Power to the load

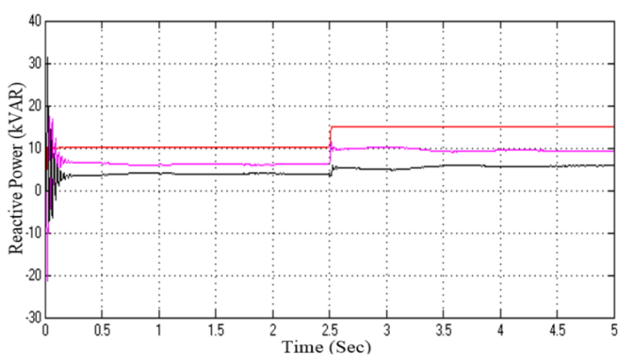

Figure 9: Reactive Power to the load

The reactive power generated by the hydro based SG, inverter and total reactive power supplied to the load has been shown in the figure (9). In this figure, we can see the inverter and SG shares total reactive demand of the load as per their size using droop characteristics. As the capacity of the load is 10 kVAR, SG (125 KVA) share 6.4 kVAR and Inverter (40 kW) share 3.6 kVAR. At 2.5 sec, a load of reactive power demand of 5 kVAR is added to the system and this added reactive demand also shares by the inverter and SG as per their sizes.

Frequency of the system is shown in the figure (10). From this graph, it can be seen that the frequency is regulated at 50 Hz. Another load is added to the system after 2.5 sec, which causes some transient in the frequency of the system, and after sometimes it stabilizes, which can be seen in the figure.

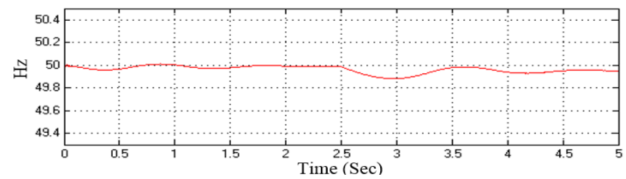

Figure 10: Frequency of the system

Waveform of ac line to ground voltage of the system is shown in the figure (11) below. From this waveform, we see that the line to ground voltage is regulated to be 400/√3 V.

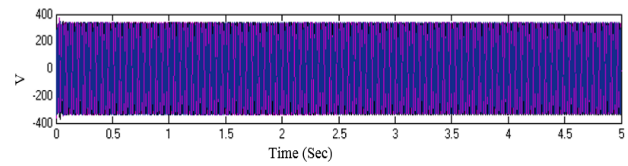

Figure 11: Voltage waveform of the system

Waveform of ac current of the system is shown in the figure (12) below. From this waveform we see that current load current increases due to addition of load at 2.5 sec.

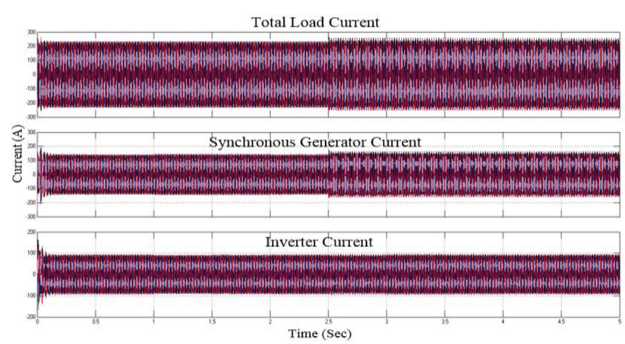

Figure 12: Current waveform of the system

Total Harmonic distortion of current waveform of the inverter is shown in the waveform figure (13) below. As per figure the total harmonic distortion is about 9% which is acceptable.

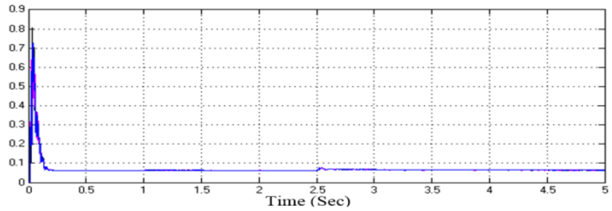

Figure 13: Total Harmonic Distortion of inverter current

7. Conclusion

In this paper an aggregate controller for isolated loads supplied by composite system of VSI and hydro based SG has been proposed. SG is operated as a voltage and frequency control mode. Frequency and voltage of the output bus is controlled by SG itself using aggregated load frequency control by governor based hydraulic turbine and excitation control respectively. Synchronization of the inverter with the SG is achieved through Phase Locked Loop (PLL). The d-q based control strategy is deployed in the inverter so that it is operated in line with the output bus of the SG. Inverter is design to extract all the available active power to the load, shares the requisite reactive power with SG using droop control mode whereas SG is operated to provide the deficit active power to the load and shares the requisite reactive power with inverter using droop control mode. The effectiveness of the control techniques of this system is validate through MATLAB based Simulink simulation under constant as well as varying load condition. This hybrid system is used to supply the unremitting power to remote isolated loads where the resources exist but unavailability of national grid. VSI is suitable for the connection of Solar PV, Wind Power or other distributed generator as per availability. Thus this hybrid system is suitable for the country like Nepal where there is abundant availability of the small hydro, and used of the VSI interfaced distributed generation like solar, wind as complement to this as per availability to meet the load demand.

Appendix

In each control loop PI(i) is used to represent the controller consisting of relevant proportional (K_p) and integral (K_i) gains as shown below,

$PI(s) = Kp + Ki/s$ where $i = 1$ *to* 5

The optimum value of gains pertinent to speed, voltage and current controllers capable of accomplishing a stable electrical power system are listed below,

$PI_1(s) = 6 + 60/s$

$PI_2(s) = 5 + 80/s$

$PI_3(s) = 1 + 50/s$

$PI_4(s) = 1 + 50/s$

$PI_5(s) = 0.5 + 0.05/s$

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