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Performance Analysis of Voltage Stability againstSudden Load Changes in Voltage Controlled Inverters for Distributed Generation

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ABSTRACT

Distributed Generation (DG) is playing an important role in the field of electricity generation by being a viable alternative to the Centralized Power Generation (CPG). This interest is also motivated by the need for eliminating the unnecessary transmission and distribution costs, reducing the greenhouse gas emissions, deferring capital costs and improving the availability and reliability of electrical networks. Although, distributed generation has many advantages, it has some issues in the fields of protection, power control, stability, islanding detection etc. Amongst all the issues, this paper attempts to highlight the issue of voltage stability under sudden changes in loading conditions in a distributed generation systems operating in stand-alone mode. Proper design and tuning of compensators for closed loop operation in DG systems can ensure voltage stability. As the load demand increases, the output voltage of DG usually dips for a short time owing to the weak (smaller capacity) nature of renewable sources, after which it returns to steady state. This fall in the voltage profile could prove to be harmful if the settling time is more. The simulation and hardware results illustrate that, accurate compensator design, is one of the key factor in maintaining the voltage stability in DG system. This paper explores the effect of proper compensator design in maintaining voltage stability of DG.

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1. INTRODUCTION

The energy industry today is facing many challenges because of the ever increasing demand of the electrical power. These challenges include maintaining power quality, increasing the power transfer capacity of the system, reducing the high capital cost required for generation of power as well as reducing the per unit cost and many more. The power electronics and power systems researchers are currently working towards the solution to these problems. The ongoing researches in this area have found that the problems associated with the conventional sources can better be solved through DG. Therefore DG is getting lot of attention as it can provide the solution to the issues related to the CPG.

Distributed Generation can be defined as localized small scale electricity generation in the range of few hundreds of kW to few MW [1]-[2]. In DG systems, the electrical power is generated using locally available renewable or nonrenewable energy sources. This power generated is first fed to the local load, if the power generation is more than the load demand then the power is fed to the grid. Based on this phenomenon there are two modes of operation of DG systems; first being grid connected mode or the grid-tied mode and second being the stand-alone mode or the islanded mode.

DG systems offer benefits like liberalization of electricity markets, standby capacity, reliability, and grid support etc [2]. DG is a tool that can help electrical suppliers to sort out problems in a liberalized market, where customer is keen on looking for the best suitable electricity service provider. The DG systems can be used for increasing standby capacity at times of peak load demand. The DG also helps in peak shaving for continuous power supply.

As every coin has two sides, DG also has benefits as well as some issues. But if these issues are solved then DG can be a viable alternative to CPG. The issues associated with a power electronic converter based DG unit include maintenance of power quality, protection, power control, voltage stability, frequency stability, islanding detection, smooth operating mode transfer etc. This paper addresses the issue of voltage stability in the context of the sudden load changes in DG system incorporating non-conventional / renewable energy sources and power electronic converters.

1.1. Overview of Distributed Generation

A typical structure of DG system is shown in Figure 1. A static transfer switch (STS) is used to separate the multiple DG units from utility grid at the PCC. In case of interruption in utility, the STS ensure the disconnection of multiple DG units from the main grid. Each DG system consists of a renewable or non-renewable energy source, an energy storage device, an inverter, and a controller. Each DG units is connected with the local load. The DG unit can operate in grid connected or stand-alone mode. In grid connected mode the DG units are connected to the utility grid, and the extra power available after feeding to DG local load will be supplied to utility. In case of any fault occurring in the utility grid, the STS at the PCC disconnect the DG units from utility grid as soon as possible.

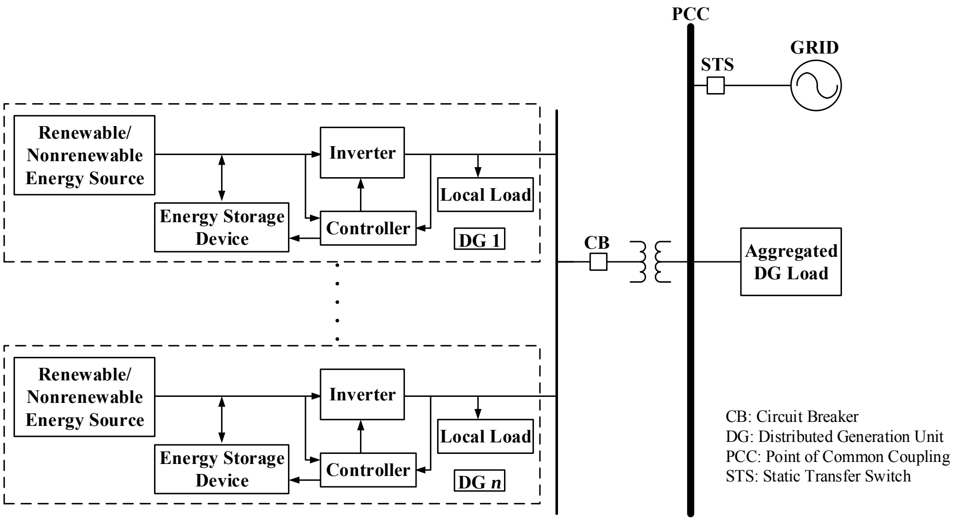


Figure 1. Structure of grid connected DG system

In the absence of the main grid the DG units can operate in standalone mode and feed real and reactive power to the local loads. Once the DG units are switched to standalone mode, the DG units immediately share the new power demand, based on the load sharing scheme implemented and supply power to all the critical loads. If the power capacity of DG units is insufficient to supply all the loads then the least important loads can be cut-off to maintain voltage stability [1]-[9].

2. LITERATURE REVIEW

Although, the DG has certain issues, it has managed to attract the researchers to find solution for them. Along with all other issues, the researchers are also dealing with voltage stability issue. In DG systems, the output voltage is controlled by controlling the reactive power control. This regulation is based on the droop control characteristics [1], [3]-[5].

The issue of voltage stability and power control becomes quite significant in stand-alone mode of operation because in this mode of operation, the DG unit has to supply both real and reactive power to the load. Also in islanded mode, when parallel DG units are feeding common load, the synchronization between phase, frequency and magnitude is difficult, which results in in-adequate load sharing between DG units [1],

[3]-[4]. This in-adequate load sharing affects the voltage profile of DG system. To overcome these issues of reactive power control and maintaining smooth voltage profile many power control strategies have been proposed. These strategies are mainly based on droop control characteristics which can be further classified as virtual impedance control [1],[3], integral control [4], voltage source control [5] etc. based on the modification in the droop control characteristics equation.

The conventional method used for real and reactive power control is droop control method. The following subsection gives background of droop control characteristics.

2.1. Droop control characteristics

To understand the origin of the concept of droop control, the complex power transferred by a transmission line needs to be considered. The single line diagram of transmission line is shown in Figure 2 as an RL circuit with the voltages at the terminals of the line.

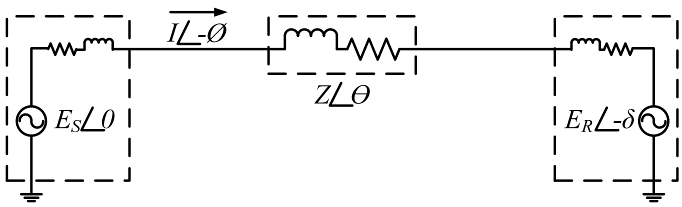


Figure 2. Power Flow through a Transmission Line [1]

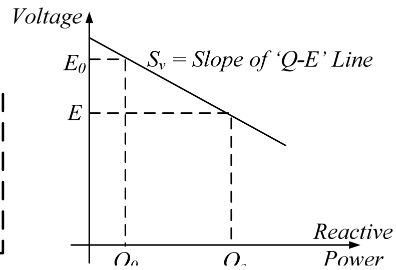


Figure 3. Reactive power control through voltage droop control [3]

Where, E_S and E_R are sending and receiving end voltages respectively, δ is angle between sending and receiving end voltages, I is current flowing through the transmission line, Φ is angle between sending end voltage and current, and Z is load impedance.

Typical transmission lines are modelled with the inductance (X) being much greater than the resistance so the resistance is generally neglected. The equation for reactive power (Q_e) can then be written as,

$$Q_e = \frac{E_S^2}{X} - \frac{E_S E_R}{X}\cos\delta \qquad (1)$$

If the power angle δ is small, then the small angle formula can be used so that cos δ = 1. Simplifying and rewriting gives,

$$E_S - E_R \cong \frac{XQ_e}{E_S} \qquad (2)$$

Equation (2) determines that voltage difference depends on the reactive power [2]-[5]. In other words, if the reactive power can be regulated, then the voltage E_S will be controllable as well. By regulating the reactive power flows through a power system, the voltage can be determined. This observation leads to the common droop control equation [10]–

$$E = E_0 - S_v(Q_e - Q_0) \qquad (3)$$

WhereE_0 is the base voltage, K_v is the slope of $Q - E$ characteristics and Q_0 is the temporary set points for the reactive power of the inverter. The typical voltage droop control characteristic plot is shown in Figure 3. From the droop equation (3) as well as from Figure 3 it is evident that, as the reactive power demand increases, the droop control scheme will allow the system voltage to decrease. The slope of the characteristic can be used to estimate reactive power required to be absorbed or pumped into the system.

2.2.Voltage Stability

Maintaining voltage stability is a very important aspect in power system. A system enters a state of voltage instability when a disturbance or increase in load demand occurs. Voltage stability may also be affected when a source is unable to meet the reactive power demand. Voltage profile can thus be defined as the change in the voltage of the system as the load changes.

The type of source used has substantial impact on the voltage profile of the DG system. The, voltage instability problem in a DG system is one of the most destructive situation on power system. A DG system when associated to a grid is not a rigid or stiff system. Hence, it is required to implement accurate control strategies for effective operation of a DG system.

Most of the DG systems with renewable sources such as PV array, wind are sometimes, depending on atmospheric conditions incapable of producing reactive power. Thus, during dynamic load changing state, they cannot maintain voltage stability. Therefore suitable voltage compensator should be designed and implemented to maintain the voltage stability of the DG system. Therefore, the integration of any DG source needs to be coordinated with the available voltage and reactive power control scheme in order to ensure that the DG system will not drop the proper voltage stability.

A flat voltage profile can be assured if

- Source supplying the power is stiff i.e., The voltage offered by the source does not dip as load demand increases.
- There is an alternate source which can pump in power at the transient state.(e.g.Ultra capacitor)

A compensator is appropriately designed to compensate for the dip in the voltage profile at times of load increase. This can include PI or PID controllers that are properly tuned.

3. HARDWARE AND SIMULATION RESULTS

The simulation and hardware implementation of DG unit in stand-alone mode of operation was performed. All the simulations were performed on MATLAB/Simulink software. The simulation results obtained were verified by implementing on a three phase inverter based DG unit hardware prototype developed in the institute's research laboratory. The simulation and hardware results are explained in detail in following subsections.

Appropriate design of compensators is crucial for proper closed loop control of any system. In the system under study, the sensed voltages are converted from abc-to-dq reference frame and then fed to the individual PI controllers. The output of PI controllers are taken as input to dq-to-abc transformation for generating corresponding pulses for driving inverter switches. Depending upon the various proportional gain K_p and integral gain K_i values the transient response of the system was found to vary.

This paper particularly focuses on the impact of different sources and compensator design on DG system. Battery, solar PV, and Fuel cell are the three types of sources considered for this impact study. The following subsections include the detailed analysis of the effect of these sources along with compensator for different K_p and K_i values.

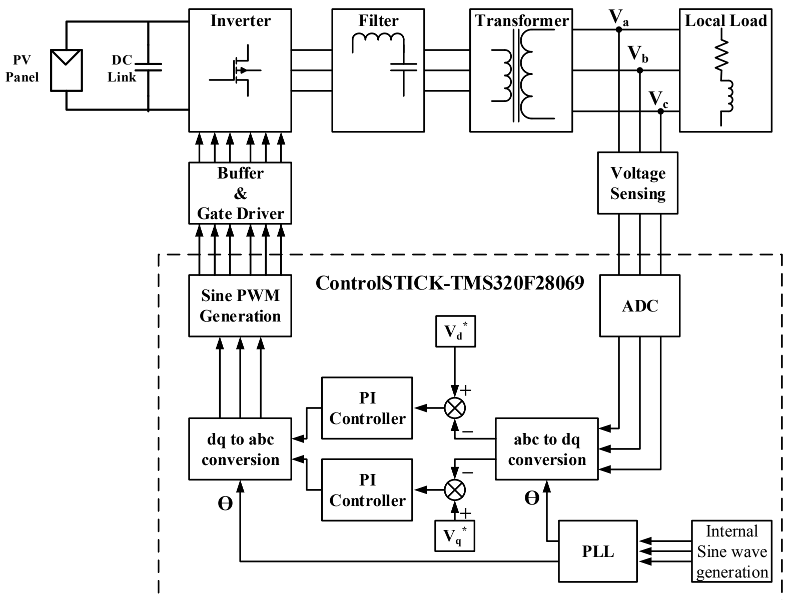


Figure 4. Closed loop control scheme for voltage controlled Stand-alone DG unit

3.1. Simulation Results

The Figure 4 shows the detailed control scheme implemented on the system under study for power control in stand-alone mode. This scheme implemented in simulation, is done for dynamically changing loads. When the load is resistive, the inverter gives a clean three phase waveform for voltage and current as shown in Figure 5, Figure 6 and Figure 8.

On the event of a sudden increase in load, the voltage profile of the DG changes depending upon two main factors; the former being the stiffness of the sources and latter based on the accuracy of the compensator design or both. Figure 6 shows the output current waveform of a voltage controlled stand-alone

DG unit on the onset of a load change. The waveforms in Figure 5 and Figure 6 shows that, the system is stable for any loadchange i.e. theoutput voltage of DG unit remains constant at specified reference value. For large load change the output voltage deviates from its reference, but due to the closed loop control scheme the voltage again restores back to its reference value in short time.

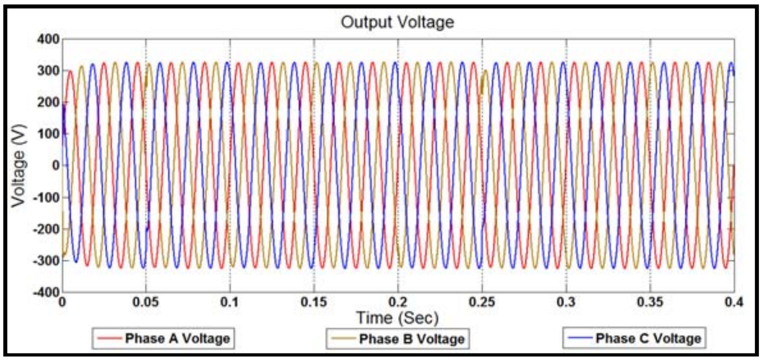


Figure 5. Voltage controlled Stand-alone DG unit output voltage waveform

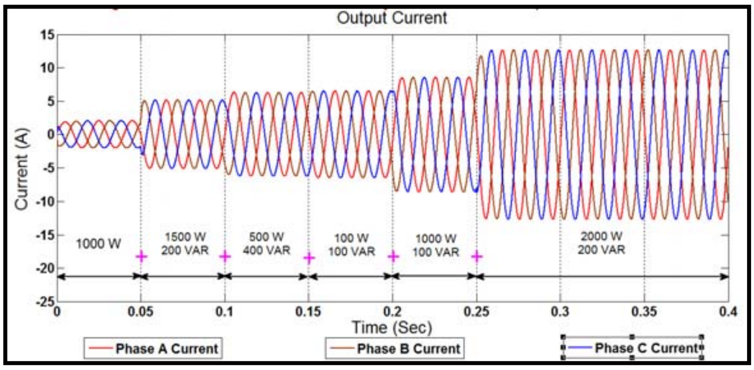


Figure 6. Voltage controlled Stand-alone DG unit output current waveform

3.2. Hardware Results

The PV source is inherently not a stiff source in the sense that it cannot supply power demanded by a load on the event of a sudden load increase. Hence the voltage profile may be affected and there would be a sudden dip in the power supplied. In order to maintain the voltage constant, an appropriate closed loop operation of the inverter is implemented through DSP as shown. The sensed voltages from the inverter output are fed to compensators that are implemented in discrete form in DSP. The controller used for implementing control scheme is DSP-TMS320F28069 control-stick from Texas Instruments. Figure 7 shows the laboratory setup for the developed prototype of stand-alone DG unit.

Appropriate design of compensators is crucial for proper closed loop control of any system. In the system under study, the sensed voltages and currents are converted from abc to dq reference frame and then fed to the individual PI controllers. Depending upon the various K_p and K_i values the transient response of the system was found to vary.

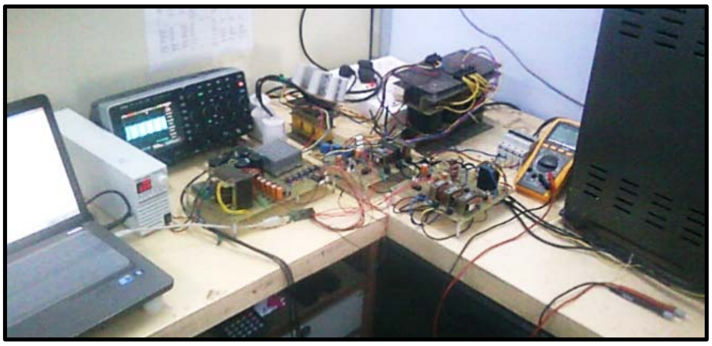


Figure 7. Laboratory setup for stand-alone DG unit

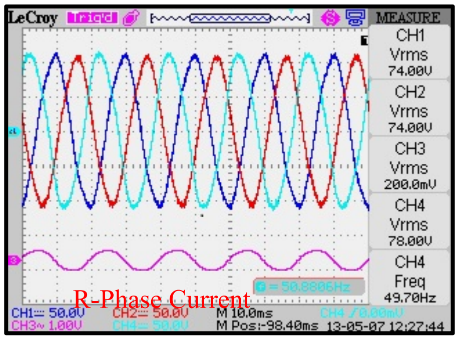
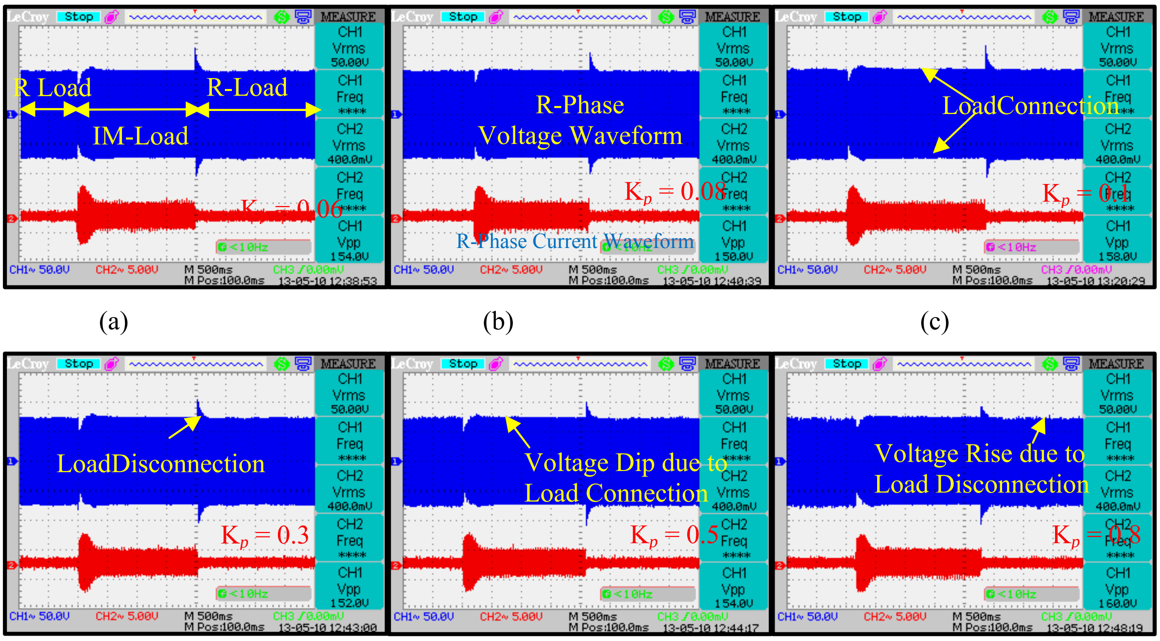


Figure 8. 3-Ø voltage and R-phase current waveform for a stand-alone DG unit.

The output voltage and current waveforms for the control scheme of Figure 4 are shown in Figure 8. The response of the DG unit on account of a load increase and load decrease are shown in Figure 9, Figure 10 and Figure 11. Initially the load connected to the system was 10 W resistive load, later a 3-Φ induction motor was connected as inductive load in parallel to resistive load. The impact of various K_p and K_i values was assessed by connecting and disconnecting IM as load.

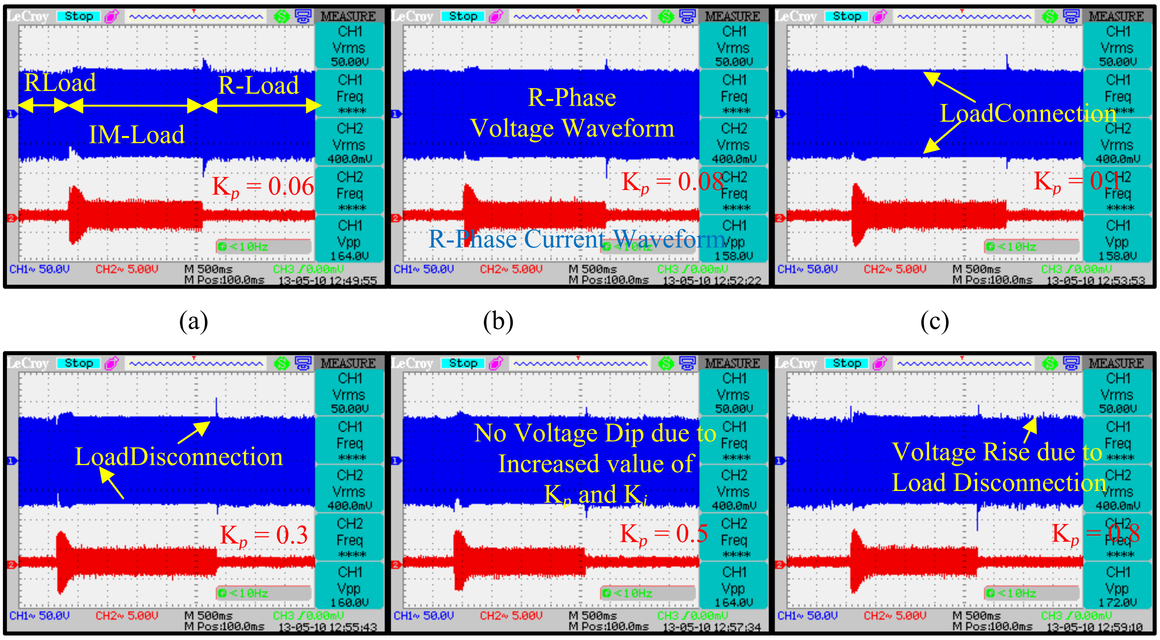
The system was tested at low voltage to measure the transient response on DSO. The primary voltage of 110V-to-415V step up (Δ-Y) transformer was adjusted to 50 V RMS. Figure 9 shows the transient response of system for inductive load connection and disconnection.



(a) (b) (c)

(d) (e) (f)

Figure 9. Transient response of system for different K_p values with $K_i = 0.001$



(a) (b) (c)

(d) (e) (f)

Figure 10. Transient response of system for different K_p values with $K_i = 0.003$

The developed hardware was tested for various combinations of K_p and K_i gain values. It is verified that the system is stable and operates in closed loop control for all these K_p and K_i gain values. The waveforms shown in Figure 9 are for different values of $K_p$with K_i = 0.001. From Figure 9 (a)-(f) it is evident that as K_p value increases, the peak amplitude of switching transient decreases, but there is negligible change in steady state time of the system. The time required to compensate for the dip occurred in voltage profile due to load connection takes almost same time for all K_p values used for testing system.

The waveforms shown in Fig. 10 (a)-(f) are for K_i = 0.003. This increased K_i value gives good transient response. It is clear from the above figures that as K_p value increases along with K_i value, the amplitude as well as transient time also reduces. Also with increased gain values the time required for the system to come to steady state at the event of additional load connection into the system is reduced. Figures explain that, the voltage dip occurred due load connection is almost vanishing and an almost flat voltage profile is obtained.

With K_p = 0.8 and K_i = 0.005, the system gives almost flat voltage profile with negligible time required for the system to restore back to steady state from transient state. The switching transients are also negligible in amplitude.

The impact of these various proportional and integral gain values on voltage controlled inverters for distributed generation are tabulated in Table 1.

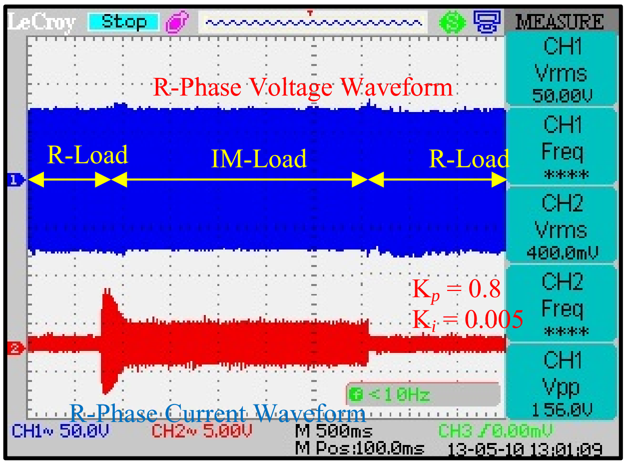


Figure 11. Transient response of system for K_p = 0.8 and K_i = 0.005

Table 1. Analysis of different compensator gain values

Proportional Gain (K_p)	Integral Gain (K_i)	Transient Amplitude	Steady State Error
0.06	0.001	Moderate	Moderate
0.08	0.001	Reduces	Small Change
0.1	0.001	Reduces	Small Change
0.3	0.001	Reduces	Small Change
0.5	0.001	Reduces	Small Change
0.8	0.001	Reduces	Small Change
0.06	0.003	Moderate	Reduces
0.08	0.003	Moderate	Reduces
0.1	0.003	Moderate	Reduces
0.3	0.003	Reduces	Reduces
0.5	0.003	Reduces	Reduces
0.8	0.003	Reduces	Reduces
0.8	0.005	Vanishes	Vanishes

4. CONCLUSION

In distributed generation system or any power system, the load attached to it is always unpredictable and continuously varying. This continuously changing load results in voltage stability issues. The moment system is loaded with additional load, it demands high starting current.To supply this high starting current initially the DG output voltage dropsand thentakes finite time to restore back to its normal operating condition depending on the compensator design i.e. maintain the DG output voltage.

The hardware results presented here determines that, if the compensator design is very accurate, then this time taken by the system to restore to its normal operating condition can be reduced, also the transient amplitude can be minimized. From the Table 1 it is concluded that, increase in proportional gain results in decrease in transient amplitude as well as increase in integral gain results in minimizing steady state error.

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