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Repetitive Control based Harmonic Voltage Compensation in Distributed Generation System

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***Abstract*— Distributed Generation refers to small-scale electric power generators that produce electricity at a site close to customers using renewable energy in remote areas. Distributed Generation system is suitable for both stand alone and grid connected systems. In standalone mode, the DG output voltage should be sinusoidal at the point of common coupling irrespective of the load variation and type of load. The design can be implemented with PI controller which is suitable for only balanced linear loads. In case of, non linear and unbalanced loads, it is difficult to maintain the DG output voltage always sinusoidal due to harmonic voltage drop in the system impedance. To overcome the drawbacks of PI controller such as slow dynamic response, poor voltage regulation and high harmonic distortions, it can be replaced by the Repetitive Controller. Repetitive Controller is a control method developed by the Japanese scholars in 1980's based on the internal model principle and is used specifically in dealing with periodic signals. The comparison of THD values using controller is estimated. The feasibility of the proposed control strategy is verified through the simulation results.**

***Keywords*— Distributed Generation, Stand alone, Repetitive Controller, Nonlinear load, Unbalanced load, Three Phase Inverter.**

I. INTRODUCTION

Due to the concerns about global warming, gas emissions and depletion of fossil fuels results in the utilization of renewable energy sources to produce electricity. Different renewable energy sources such as wind turbines, photovoltaic, fuel cell etc. are combined into the power distribution system through power electronic converters in the form of Distributed Generation (DG) [1]. DG systems are mainly developed for grid-connected operation with various functions such as power control, harmonic current mitigation and reactive power compensation. Due to the demand in supplying the power to the rural areas and non electrification villages, the concept of standalone system is majorly used [2]. In standalone system, DG must deliver the sinusoidal voltage to loads at point of common coupling with a constant magnitude and frequency. Due to the absence of stiff grid in the standalone operation of Distributed Generation system, the quality of the DG output voltage strongly depends on the performance of the voltage control strategy. The quality of the DG output voltage is mainly evaluated by the steady-state error and dynamic performance under different load conditions [3]. And also the total harmonic distortion (THD) should also be considered to evaluate the DG output voltage performance for both non linear and unbalanced load conditions. The photovoltaic system connected with variable load conditions in standalone mode includes the control of inverter to maintain the load under different conditions and the PWM technique is applied on the inverter to normalize the voltage unbalance during variable load [4]. Three-phase PWM voltage inverters in single stand-alone ac distributed generation system allows the elimination of unwanted harmonics from the output voltages under severe nonlinear load conditions [5].The concept of inverter in the utilization of renewable energy sources effectively with SPWM control of inverter. This represents the SPWM technique for harmonic reduction and generation of SPWM switching signal using three phase PWM voltage source inverter [6].

The schematic diagram of the standalone distributed generation system connected with the non linear and unbalanced loads is shown in Fig.1.To achieve the sinusoidal supply voltage with high quality performance at the load consumer side, many control strategies have been developed [7-12]. The control method using PI controller in synchronous reference frame is sufficient to provide the sinusoidal DG output voltage for balanced linear loads and in case of nonlinear and unbalanced load and it fails to maintain sinusoidal nature and produces harmonic voltages due to its limitation of the control bandwidth [7].

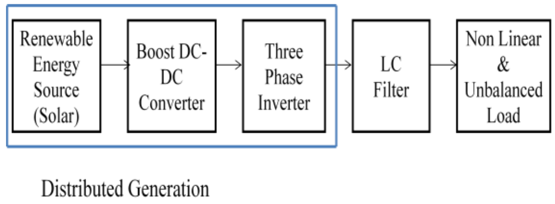

Fig 1: Block Diagram of Standalone Distributed Generation

In order to overcome this issue, several advanced control methods have been proposed. To supply pure sinusoidal voltage, many PI controllers in Multiple Reference Frame is used which supplies the sinusoidal DG output voltage under non linear load condition. Each PI controllers are used to regulate the magnitude of single harmonic voltage. Each controller need separate co-ordinate transformation to compensate the harmonic voltages which makes this method more complex [8]. The predictive control method is proposed which replaced by the bank of PI controllers and it achieves good control performance and fast dynamic response. And the performance of the predictive controller depends heavily on the system parameters. Hence it causes the system uncertainties and also affects the control accuracy [9]. An adaptive control strategy is proposed which improves the dynamic response of the controller and there is need of load current observer to estimate the load current variations and inverter current measurement is required which increases the complexity. In addition it also describes the effect of change in output voltage with the load step variations [10]. The concept of Multiple Resonant Controllers is developed for both unbalanced and nonlinear loads. These controllers are implemented stationary reference frame so co-ordinate transformations are eliminated each resonant controller compensate the harmonic voltage so large number required to compensate large harmonic voltages. This method has drawback of requiring additional current control loop and separate load current measurement [11].

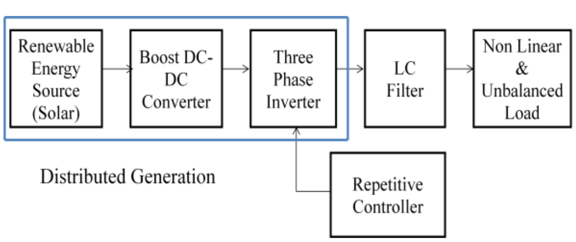

Fig 2: DG using Repetitive Controller with various loads.

To overcome these complexities, an advanced control method with repetitive controller is designed which provides an effective solution for tracking the periodic reference signals or eliminating periodic disturbances. It eliminates dominant odd harmonic frequencies under sudden load change [12]. The Repetitive Controller offers good steady-state performance and very fast dynamic response to overcome the slow dynamic response issue of traditional RCs. RC is only suitable for application to three-phase nonlinear loads which eliminates the dominant harmonic components in three-phase systems. i.e., ($6n\pm1$)th (n=1, 2, 3…). If single-phase nonlinear loads and unbalanced loads are used in the system, the performance of the control strategy is deteriorated due to the presence of other harmonic components such as third, ninth, fifteenth, etc. [13]. The design of the repetitive controller is based on the three important parameters such as controller gain, filter design and feedback controller. This method is used to improve performance of repetitive control systems by enhancing the rejection of high frequency harmonic disturbances by extending the bandwidth of filter in repetitive design [14]. The application of repetitive controller to compensate harmonic currents of nonlinear loads connected to the mains and it also achieve reactive-power compensation and mains-current balancing when required. It uses a plug-in discrete-time repetitive algorithm for current-harmonic compensation, a proportional–integral algorithm to maintain the dc-capacitor voltage and also uses state-feedback with integral action for current control. It performs the compensation of selected harmonics using a closed-loop repetitive-based control scheme based on a finite-impulse response digital filter [15]. In this paper, the enhanced harmonic voltage compensator using Repetitive Controller is discussed.

II. DISTRIBUTED GENERATION SYSTEM

A. Distributed Generation

Distributed generation refers to small-scale electric power generators in the range of 1 kW – 50 MW that produce electricity close to the customers or electric distribution system. Distributed Generation is an electrical generator or static inverter that produces alternating current which has the capability of parallel operation with distribution system, and to operate separately from the utility electrical system by feeding a load. DG systems allow customers to produce electric power by their own electric generation systems rather than traditional power plants such as coal and nuclear. Most countries generate electricity in large centralized power plants such as coal, nuclear, solar and hydro. These plants have good scale of generation, transmit electricity for longer distances but it harmfully affects the environment. Distributed generation allows collection of many renewable energy sources and provides low environmental impacts.

Small scale generating renewable energy technologies such as Solar, Wind, and Hydro etc. that are connected to the electric grid are called as Distributed Generation System. This system allows the customers to produce the electricity depending on the demand on utilization. Renewable DG systems are able to provide power with nominal impact on the environment. Most renewable DG systems produce power when the natural energy sources are available. Due to the intermittency of the power supply from DG systems, customer needs to receive electricity from the electric grid. So when DG system produces more power than the customer's load, the excess power is sent back to the electric grid. This reduces the overall electric load that the grid needs to supply.

Connecting the utility grid to remote areas require transportation of electricity over long distances to isolated population. To overcome this, DG system provides more cost-effective electrification than grid connection for remote areas. DG system can be used for standby and emergency generation, increased reliability, less costly and eliminates the need for large construction. The benefits of DG include lower capital cost, reduce the need for large infrastructure, and reduce demands on T&D lines and produces low pollutant emissions.

B. Stand Alone Distributed Generation

Stand alone system is the one in which the small renewable energy system produces the electricity that is not connected to the electric grid. Stand-alone Distributed Generation systems can be more cost-effective than the grid connected electrification for remote areas. For rural and remote villages, stand alone systems are well suited for the electric power generation. Stand-alone systems are also used by the people residing near the grid and looking for independence from the power provider and engaged to non-polluting energy sources. Batteries and other conditioning equipments are also required for stand-alone energy systems. The advantage of standalone system is to generate reliable power, reduce costs, and minimize inconvenience.

With a standalone system, solar panels are not connected to the grid and are used to charge the batteries. These batteries store the power produced by the panels and then loads draw their electricity from these batteries. The battery provides electricity on demand for electrical applications regardless of intermittency of renewable energy. Small stand-alone charging systems are suitable for remote households in developing countries. Larger stand alone systems are also available, with diesel generator to ensure that the batteries are always charged and also have high power availability.

III. HARMONIC VOLTAGE COMPENSATION

A. Effect of Variable Loads on DG output Voltage

The schematic diagram of the Standalone Distributed generation connected to the non linear and unbalanced loads is shown in Fig 2. Let R_f , L_f , I_L and V_i be the resistance, inductance, output current and inverter output voltage of the distribution generation system respectively. Then the DG output voltage V_L can be found as,

$$V_L = V_i - R_f I_L - L_f I_L \frac{dI_L}{dt} \qquad (1)$$

When the non linear and unbalanced loads are connected to the system, then the load draws harmonics into the system thus makes the system unbalanced. Hence the DG output voltage consists of both fundamental and harmonic components of inverter voltage V_{i1} , V_{ih} and load current I_{L1} , I_{Lh} respectively is given by equation (2)

$$V_L = \left(V_{i1} - R_f I_{L1} - L_f I_{L1} \frac{dI_{L1}}{dt}\right) - \left(R_f \sum_{h=2,3..} I_{Lh} + \right.$$

Lf h=2,3..dILhdt

From the above equation, it can be seen that the inverter generates pure sinusoidal output voltage, due to the harmonic voltage drop on line impedances the DG output voltage becomes distorted and produces harmonics. To eliminate harmonics and to maintain DG output voltage as sinusoidal, the inverter should compensate all the harmonics produced due to the impedance drop which is represented by,

$$V_i = (V_{i1}) + \left(\sum_{h=2,3..} V_{ih}\right) \qquad (3)$$

Due to the line impedance drop the system produces harmonics which consists of third order harmonics, to produce sinusoidal output voltage the harmonic voltage compensator needs to be regulated to mitigate these harmonics irrespective of use of single phase / three phase non linear loads and unbalanced loads.

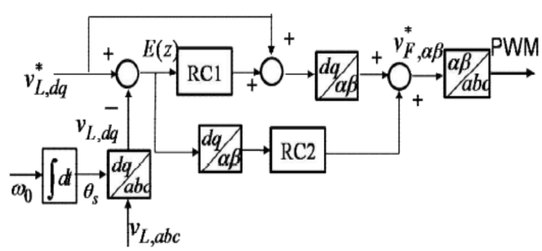

Fig 3: Harmonic Voltage compensator using RC

B.Harmonic Voltage Compensation Method

An enhanced harmonic voltage compensator is proposed to achieve sinusoidal output voltage under both non linear and unbalanced loads which consists of two repetitive controllers RC1and RC2 .The block diagram of harmonic voltage compensator is shown in Fig 3. In this proposed control strategy, one RC is designed in the rotating reference (*d-q*) frame rotates at the fundamental frequency to compensate the (6*n*±1)th (*n*=1, 2, 3…) harmonics and the other RC is designed in the stationary reference (*α-β*) frame to compensate triplen harmonics such as the third, ninth, fifteenth, etc. Hence as a result, the DG output voltage is regulated to be a sinusoidal waveform irrespective of the presence of single-phase and three-phase nonlinear and unbalanced loads. With the use of two RC's, it is proved that it can compensate all odd harmonics, achieve sinusoidal DG output voltage and maintain sinusoidal nature under different load conditions. This proposed compensator offers good steady-state performance and fast dynamic response of the DG output voltage under various load conditions.

IV. REPETITIVE CONTROLLER

A. Structure of RC

Repetitive Controller (RC) is a control method developed by the Japanese scholars in 1980's and is majorly used in all engineering applications such as robotics, magnetic and optical storage devices, motors, rolling processes and rotating mechanisms. It is used specifically in dealing with periodic signals. Repetitive Controller is based on Internal Model Principle for tracking periodic reference or rejecting periodic disturbances. The common structure of Repetitive Controller is shown in Fig 4. Repetitive controller is proposed in such a way to eliminate the odd harmonics in the system.

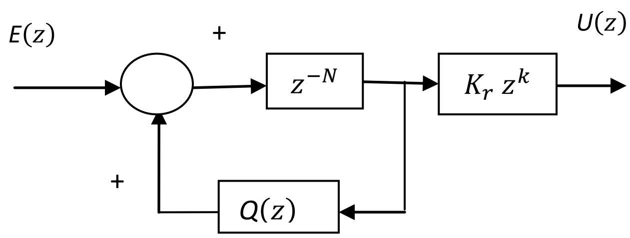

Fig 4: Structure of Repetitive Controller

The Controller transfer function can be given as,

$$C(z) = \frac{K_r\, z^{-N+k}}{1-Q(z)z^{-N}} \qquad (4)$$

where z^{-N}- Time delay z^{k} - Phase Lead term, Q(z) - Filter, K_r - Gain of the controller, E(z) – Error Value , U(z) – Output of the Controller and N – No. of samples and defined as the ratio of the sampling frequency to the fundamental output frequency.

The design of RC mainly depends on these parameters such as Filter Q(z), Phase lead term z^k, RC Gain K_r and Time delay Unit z^{-N}. The proposed harmonic voltage compensator consists of two repetitive controllers. RC1 in synchronous reference (d-q) frame rotates in fundamental frequency to compensate (6n±1)th harmonics which is given by the transfer function,

$$C_1(z) = \frac{K_{r\,1}\, z^{-\frac{N}{6}+k}}{1-Q(z)z^{-\frac{N}{6}}} \qquad (5)$$

With RC1, it is able to compensate the odd harmonics caused by only three phase non linear loads and it fails to maintain the sinusoidal DG output voltage due to the presence of the triplen harmonics when connected to the single phase non linear and unbalanced loads. Hence there is need of another RC which is suitable for both non linear and unbalanced loads.

RC2 in stationary reference (α-β) frame to mitigate triplen harmonics such as third, ninth, etc. and its transfer function is given by,

$$C_2(z) = \frac{K_{r\,2}\, z^{-\frac{N}{6}+k}}{1+Q(z)z^{-\frac{N}{6}}} \qquad (6)$$

Both RC1 and RC2, compensate the odd harmonic voltage drops caused by non linear and unbalanced loads by ensuring that the DG output voltage is maintained always sinusoidal.

B. Design of RC

In the design of Repetitive Controller, three important parameters are to be considered for the effective solution of eliminating the odd harmonics. Based on the frequency domain and Nyquist Plot the RC design plays a major role. The main components are chosen as follows and are determined based on the system parameters.

Filter Q(z) is chosen as low pass filter to improve the system stability margin by reducing the gain of the controller at high frequencies and the filter transfer function is given by,

$$Q(z) = \frac{z^2+2z+1}{4z} \qquad (7)$$

The Phase lead expression Zk is utilized to compensate the phase lag in the system and k value is chosen in order to minimize the phase displacement by the plant and the value is taken as 3 for the harmonic order up to 31st.

The LC filter transfer function is given by,

$$G_p(s) = \frac{1}{L_f\, C_f\, s^2 + R_f\, C_f\, s+1} \qquad (8)$$

Based on Nyquist plot shown in Fig 5 ,the controller gain Kr=1.5 is chosen because the system is stable only if Kr is less than 1.8 which provides the sufficient stability margin and N is the number of samples and is selected as 12 depending on the sampling frequency.

When two cases with non linear load and unbalanced load are considered, the results are found with high THD without any compensation on the system, the DG output voltages are shown in Fig 7 and Fig 8.

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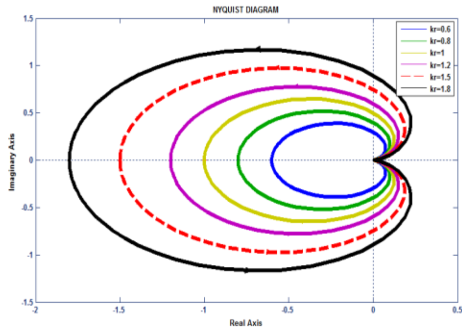

Fig 5: Nyquist Plot for determining K_r gain of the controller.

V. SIMULATION RESULTS

The simulation model of the Distributed Generation system has been carried out by MATLAB and is shown in Fig 6 and the results are verified.

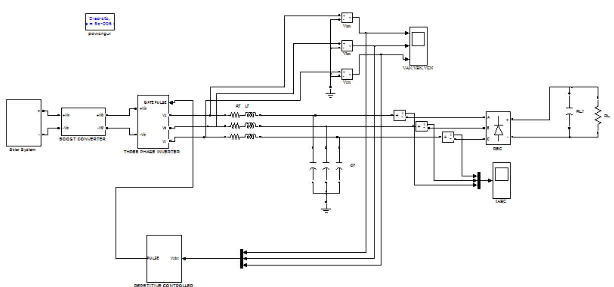

Fig 6: Simulink diagram of DG system using RC

In order to reduce the harmonics, the compensation using repetitive controller is carried out and the performance of the DG output voltage is studied. With one RC it is capable of providing good steady state performance of the DG output voltage when a non linear three-phase diode rectifier load is used as shown in Fig 9 .And it fails to maintain sinusoidal output voltage when unbalanced load is connected. Thus RC2 is used for single phase non linear loads and unbalanced loads to eliminate triplen harmonics and the DG output voltage is shown in Fig 10. It is clear that the proposed strategy with two RC's can provide good performance of the DG output voltage.

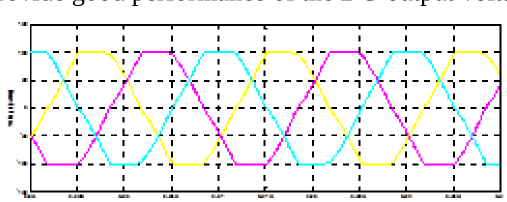

Fig 7: Output Voltage of non linear load without RC

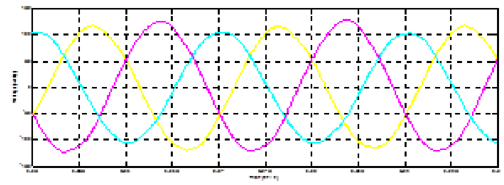

Fig 8: Output Voltage of unbalanced load without RC

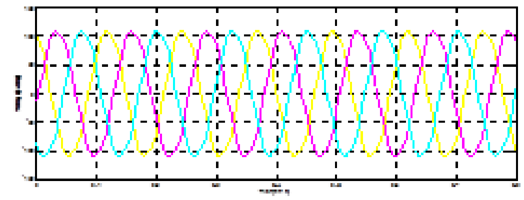

Fig 9: Output Voltage of non linear load with RC

This control strategy produces high controller gain at the ($6n\pm1$)th harmonics and triplen harmonics . Hence it effectively compensates all odd harmonic voltage drops and regulates DG output voltage to be almost sinusoidal under various load conditions.

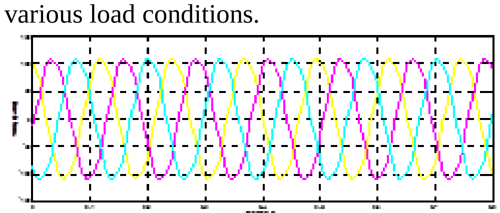

Fig 10: Output Voltage of unbalanced with RC

TABLE 1: SYSTEM PARAMETERS

Parameters	Values
Reference Output Voltage	110V (RMS)
Switching Frequency	50HZ
Filter Inductance	2mH
Filter Capacitance	500μF
Non Linear Load	R= 30 Ω, C=2200μF
Unbalanced Load	R= 10,20,30 Ω L=2,4,6mH

TABLE 2: COMPARISON OF THD VALUES

Type of Load	***Phase Voltages in %***	***Without Controller***	***With RC***
Non Linear load	Va	5.86	0.27
	Vb	5.92	0.26
	Vc	5.78	0.29
Unbalanced Load	Va	22.38	0.54
	Vb	21.96	0.52
	Vc	22.57	0.50

From the simulated results, it can be concluded that the proposed controller offers excellent steady-state performance, faster dynamic response and THD value of the DG output voltage lower than 1% under various load conditions. A summary of the THD value of the DG output voltage is shown in Table 2.

VI. CONCLUSION

In this paper, harmonic voltage compensator for standalone distributed Generation system consists of two Repetitive Controllers is analyzed and the results are obtained. From the results, it is proved that by designing RC1 it compensates ($6n\pm1$)th harmonics and RC2 compensates triplen harmonics and hence the proposed harmonic voltage compensator is capable of compensating all odd harmonics with fast dynamic response and good steady state performance. The main objective is achieved by maintaining the DG output voltage to be sinusoidal with low THD under different load conditions including single-phase, three-phase nonlinear and unbalanced loads with the help of two RC's in the proposed harmonic voltage compensator for the stand alone Distributed Generation System.

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