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Flexible GTVSG Power Quality Enhancement Using Resilient Heterogeneous Voltage and Current Control

Sameer Kumar Behera
Dept. of Electrical Engineering
National Institute of Technology, Rourkela
Email:- 519EE1003@nitrkl.ac.in

Anup Kumar Panda
Dept. of Electrical Engineering
National Institute of Technology, Rourkela
Email:- akpanda@nitrkl.ac.in

N. Venkataramana Naik
Dept. of Electrical Engineering
National Institute of Technology, Rourkela
Email:- nenavathv@nitrkl.ac.in

Swapnajit Pattnaik
Dept. of Electrical Engineering
National Institute of Technology, Raipur
Email:- spattnaik.ele@nitrr.ac.in

Prerana Mohapatra
Dept. of Electrical Engineering
National Institute of Technology, Rourkela
Email:- prerana_mohapatra@nitrkl.ac.in

Markala karthik
Dept. of Electrical Engineering
National Institute of Technology, Rourkela
Email:- 521EE7006@nitrkl.ac.in

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***Abstract*—This article proposes an resilient heterogeneous voltage and current control scheme (RHVCS) for a three-phase grid-tied virtual synchronous generator (GTVSG) system to provide harmonic compensation and consequently improve the system's power quality. The GTVSG system, as mentioned above, incorporates renewable energy-based distributed generation units (REDG) profoundly photovoltaic generators (PVGs) on the source terminal, having dynamic input characteristics. Considering the control aspects for GTVSG, it adopts various current and voltage control methods discussed in the literature. However, the proposed RHVCS implemented in the GTVSG digital controller helps reduce the number of lowpass/band-pass filter involved. Furthermore, the proposed controller uses a phase lock loop (PLL) less strategy which automatically necessitates the identification of the deviation in the GTVSG system frequency from the power control loop. The proposed RHVCS incorporates three different harmonic compensation objectives illustrated in different sections. Additionally, the proposed control strategy minimizes the digital controller's complexity without infringing on the harmonic compensation's performance, which is commendable. Finally, the above controller is implemented in MATLAB/Simulink platform**

Keywords— Power quality, virtual synchronous generator control, LCL filter, resonant controller, virtual impedance, harmonic compensation.

I. Introduction

THE increase in global warming caused by environmental pollution has led to the shift in energy sources from conventional sources to non-conventional sources. To have a carbon emission-free environment, dependency on renewable sources like PVG has increased enormously, giving rise to two major issues:-

1. The massive PVG penetration into the conventional grid-tied systems (GTS) results in a low inertia grid and,
2. Extensive PVG usage with nonlinear loads and interfacing power-electronics converters (IPEC) introduces harmonics, impacting power quality in the utility grid with voltage and current distortions.

An introduction to a combined concept of VSG and virtual inertia helped researchers to address the first issue, where the former emulates the external characteristics being incorporated both in the active power loop (APL) and reactive power loop (RPL) of a conventional synchronous generator [1]. The latter provides additional active power support during transient disturbances through the energy storage unit (ESU), which improves the frequency response and, thereby, increases the stability of the power system. Now, to resolve the second issue, literature has evidence of numerous active power-filtering methods, as mentioned in [2]-[3]. The IPEC-based DGs in GTS offer improved power quality with a broader bandwidth compared to conventional distributed synchronous generators, eliminating the need for additional harmonic filtering unit [4]. Moreover, the IPEC-based DGs are predominantly remote-based, with non-ideal conditions prevailing in the grid; therefore, distorted grid currents and voltages are attained with an enhancement in nonlinear loads and huge penetration of renewables. These distorted grid components deteriorate the power quality and system stability, apprehending inappropriate VSG application [5]. The control schemes implemented in REDG-based GTS units are typically classified into two categories, the current-controlled method (CCM) and the voltage-controlled method (VCM), as mentioned in [6].

Furthermore, VCM is more advantageous over CCM on dual operating modes, i.e. (grid-tied and islanded modes) in micro-grid applications. Considering other aspects of controller, an effective, robust control scheme for the mitigation of resonances in grid-connected converters has been illustrated in [7]. A robust hysteresis controller design is described in [8], which provides a rapid, selective harmonic compensation method in inverter control with the added advantage of reducing computational load.

Significantly, an assembly of REDG virtual impedance shaping and virtual synchronous generator (VSG) control ensures communication-free load sharing between REDG units in micro-grid islanded mode [9]. However, considering the conventional VCM, regulating the REDG unit line current becomes problematic. A better approach towards the realization of power quality of micro-grid, an improved VCM (IVCM) approach with point of common coupling (PCC) harmonic voltage feedforward term, was proposed in [10].

Perpetuating all the advantages of the CCM and VCM, an enhanced REDG control strategy simultaneously controlling the PCC voltage and line harmonic current in [11] proposes a hybrid voltage and current control scheme (HVCS). The voltage and current control branches in HVCS have dedicated control for fundamental PCC voltage and REDG line harmonic current, respectively. Analogous to VCM, the control loops of power (droop control) and virtual impedance is mentioned in [12], whereas in [13], a reference voltage signal for the voltage control branch is provided. Harmonic current introduced by the local nonlinear loads in [14] was addressed using HVCS. Moreover, an interaction amongst PCC shunt capacitor banks and inductive grid feeders possibly will produce some resonances even after proper compensation of nonlinear loads by HVCS. The variation in frequency is a major concern in a micro-grid system, due to voltage disturbances in utility grid or the impact of sudden load changes. So, under the assumption of fixed micro-grid fundamental angular frequency design of a current control branch, leads to inappropriate control of REDG harmonic current.

In this article, considering the inertia of the grid to be a major factor, VSG technique is adapted to get a better understanding of the disturbances in the three phase utility grid. Furthermore, the micro-grid harmonic compensation approach using adaptive angular frequency in the proposed RHVCS. To begin with, the VSG technique incorporated with real and reactive power control is integrated into the GTS. In contradiction to [15]-[19], which predominantly uses phase lock loops (PLL) to regulate the microgrid angular frequency, the reference frequency signal acquired from the VSG control is directly embraced as the time-varying parameter of the proposed control strategy, thereby making it frequency adaptive. Moreover, the proposed harmonic compensation strategy is researched further to streamline the virtual impedance and power control loops.

The main contributions of the proposed RHVCS control scheme are:-

- ❖ The RHVCS control technique makes the system frequency adaptive and thereby decreases the computational complexity of the digital controller.
- ❖ The control technique eliminates the necessity of PLL as the micro-grid frequency variation is automatically identified by the power control loop.
- ❖ The control technique enhances the dynamics of the three-phase GTVSG system by improving the voltage and current profile of the system during transients.
- ❖ The proposed control technique maintains unity power factor (UPF) on the grid side always.
- ❖ It helps in compensating the grid side, grid load side, local load, and PCC voltage harmonics.
- ❖ It also reduces the number of harmonic filtering units and low-pass filters from the REDG system, making it cost-effective.

The further sections of this paper are coordinated as follows. Three-phase GTVSG's constant angular frequency resonant controller-based RHCM is established in section II. Section III describes the proposed adaptive HVCS for the GTVSG system. Section IV introduces a prototype of the proposed method to verify its correctness. At last, the conclusion is in the last section.

II. Constant Angular Frequency Resonant controller-based RHCM

A. Three-phase GTVSG power control Loops

The basic configuration of three-phase GTVSG is illustrated in Fig. 1, where the REDG unit is integrated into a GTS at the PCC through IPEC and an LCL filter. The presence of local loads connected across the output terminal of the LCL filter and grid loads is shown in Fig. 1. Concerning the injection of controllable power to the micro-grid, the adaptive active power control loop (AAPL) and adaptive reactive power control loop (ARPL) are incorporated to form the three-phase GTVSG power control loops.

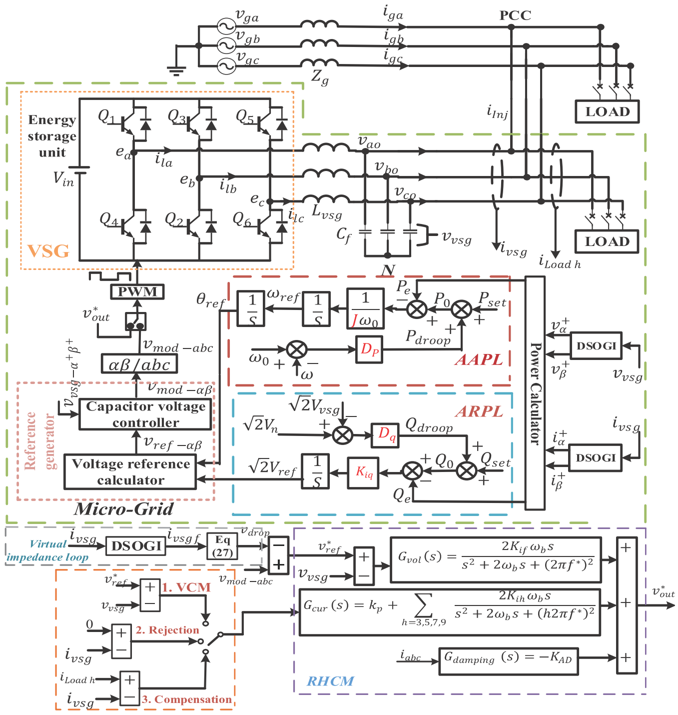

Fig.1 Schematic equivalent of three-phase GTVSG.

First of all, instantaneous active and reactive power (P_e and Q_e) calculator is obtained as:-

$$P_e = \frac{3}{2}\left(v_\alpha^+ . i_\alpha^+ + v_\beta^+ . i_\beta^+\right) \quad (1)$$

$$Q_e = \frac{3}{2}\left(v_\beta^+ . i_\alpha^+ - v_\alpha^+ . i_\beta^+\right) \quad (2)$$

where v_α^+ and v_β^+ are the positive sequence filter capacitor voltage and its corresponding orthogonal component. Similarly, i_α^+ and i_β^+ illustrates positive sequence REDG line current and its corresponding orthogonal component respectively. The aforementioned positive sequence voltage and current components are obtained from a positive sequence calculator (PSC) comprising DSOGI and a power calculator unit. The three-phase voltages and currents are converted into alpha and beta forms where beta represents the orthogonal components. The calculated active and reactive power from the AAPL and ARPL control is obtained as

$$\frac{1}{J\omega_0}\int[(P_{\mathrm{set}} - P_e).H_{LF}(s).M_P - D_P(\omega - \omega_0)] = \omega_{\mathrm{ref}} \quad (3)$$

$$K_{iq}\int\left((Q_{set} - Q_e).H_{LF}(s).(M_q + \tfrac{k_E}{s}) - \sqrt{2}D_q(V_{vsg} - V_n)\right) = \sqrt{2}V_{ref} \quad (4)$$

P_{set}, Q_{set}, P_e and Q_e represent active power reference, reference reactive power, the real power of a GTVSG, and reactive power of GTVSG respectively. M_p and M_q are the active power and reactive power droop gain, respectively. The reactive power integral control gain k_E helps in eliminating the control errors when operated in a grid-tied mode. To note k_E should be set to null value whenever the REDG shifts to islanding mode autonomously. D_q, k_{iq}, D_P and J represents the droop coefficient of reactive power, the regulator coefficient of reactive power, the damping coefficient of active power, and the virtual inertia. ω_0, ω_{ref} and ω represent nominal angular frequency, angular frequency reference and angular frequency of capacitor voltage. V_{vsg}, V_n, V_{ref} *and* θ represent the amplitude of capacitor voltage/grid voltage/voltage reference, and the angle of a TPVSG, respectively. The voltage references in the $\alpha\beta$ frame $v_{ref,\alpha} = \sqrt{2}V_{ref}\cos\theta_{ref}$ and $v_{ref,\beta} = \sqrt{2}V_{ref}\sin\theta_{ref}$. An appropriate design regulation of capacitor voltages' control loop, helps to accurately track the voltage references.

A first-order low-pass filter is selected in this paper as

$$H_{LF}(s) = \frac{\omega_{LF}}{s+\omega_{LF}} \quad (5)$$

Where, ω_{LF} represents cutoff angular frequency. The above low-pass filters $H_{LF}(s)$ is implemented for filtering out the ripples from the obatined instantaneous active and reactive power (P_e and Q_e) are mentioned in (3) and (4), respectively. With the ω_{ref} described in (3) and voltage magnitude reference V_{ref} in (4), the instantaneous value of reference voltage $v_{mod,abc}$ are analytically obtained from the reference generator illustrated in Fig. 1.

B. Intermediary Virtual Impedance Loop of a GTVSG

The power control strategy mentioned in (3) and (4) are formulated under the following assumption of an inductive REDG equivalent impedance considered in the GTVSG system. To offset the effects of resistive feeder under certain direct-coupled REDG's employing output LC filters, an inductive virtual impedance generated by control of the interfacing power converter. This approach mimics virtual impedance behavior, with its associated voltage drop v_{drop} calculated as

$$v_{drop} = R_{vf}i_{vsgf} - 2\pi f^{*}L_{Vf}i_{vsgf,delay} \quad (6)$$

where, R_{vf} and L_{Vf} are the virtual resistance and inductance obtained using the REDG controller. i_{vsgf} represents the fundamental current and $i_{vsgf,delay}$ generated by delaying the fundamental current for a quarter fundamental cycle. The fundamental current i_{vsgf} in (6) is derived from DSOGI.

$$i_{vsgf} = \text{DSOGI} * i_{vsg} \quad (7)$$

The drop in voltage drop due to virtual impedance is deducted from $v_{mod-abc}$ as

$$v_{ref}^{*} = v_{mod-abc} - v_{drop} \quad (8)$$

Where v_{ref}^{*} represents the revised voltage reference.

C. Fixed Angular Frequency HVCS Controller

The HVCS controller using fixed angular frequency demonstrated in Fig.1 contains three control branches as

$$v_{out}^{*} = G_{vol}(s)\left(v_{ref}^{*} - v_{vsg}\right) + G_{cur}(s).\left(i_{ref} - i_{vsg}\right) + G_{AD}(s)i_{abc} \quad (9)$$

Where, the voltage control branch $G_{vol}(s)$ is incorporated to comprehend closed-loop control of the fundamental capacitor voltage, a current control branch $G_{cur}(s)$ focuses to adjust the REDG line harmonic current and the last term $G_{AD}(s)$ represents an active damping term. With reference to [20], HVCS work's in three different power quality control modes. The HVCS control branches are given as

$$G_{vol}(s) = \frac{2K_{if}\omega_b s}{s^2+2\omega_b s+(\omega_0)^2} \quad (10)$$

$$G_{cur}(s) = k_p + \sum_{h=3,5,7,9}\frac{2K_{ih}\omega_b s}{s^2+2\omega_b s+(h\omega_0)^2} \quad (11)$$

$$G_{AD}(s) = k_{AD} \quad (12)$$

Where K_{if} represents fundamental regulator gain and K_{ih} represents resonant regulator gain. ω_b represents the bandwidth of the resonant regulator, h represents harmonic order, k_p represents a proportional gain in the current control branch and k_{AD} represents a proportional gain of the active damping branch.

III. PROPOSED ADAPTIVE HVCS FOR GTVSG SYSTEM

A. Modified Power Control Loop of GTVSG

The control technique mentioned in the former section was obtained with an assumption of the fixed angular frequency of the grid-tied GTVSG system. The present section discusses the REDG revised controller to control the impacts of variable GTVSG system frequencies. Furthermore, the controller complexity is mitigated by flexible utilization of the proposed HVCS.

The active power control in (3) achieves zero steady-state error with a fixed nominal value of angular grid frequency of ω_0, during grid-tied operation. To accurately control the active power in the grid-tied REDG system when disturbances in angular grid frequency occur, a solution to the above problem involves an integral term being added to the AAPL. Hence, the revised AAPL and ARPL transform to

$$\frac{1}{J\omega_0}\int\left[(P_{\text{set}} - P_e).H_{LF}(s).\left(M_P + \frac{k_f}{s}\right) - D_P(\omega - \omega_0)\right] = \omega_{\text{ref}} \quad (13)$$

$$K_{iq}\int\left((Q_{set} - Q_e).H_{LF}(s).(M_q + \frac{k_E}{s}) - \sqrt{2}D_q\left(V_{vsg} - V_n\right)\right) = \sqrt{2}V_{ref} \quad (14)$$

Where, k_f active power integral control gain. As similar to k_E, k_f is operational in grid-tied mode and during islanded operation, its value is set as zero. The integral control as mentioned in (13) helps in maintaining zero steady-state error during angular grid frequency variation. As per literature [21], the deviation in angular grid frequency in the power system becomes sluggish even during synchronous generator failure. Furthermore, a recent development in technology has led to the implementation of virtual synchronous generators (VSG) [22], capable of addressing variation of frequency adaptively in a grid integrated micro-grid system. An adaptive virtual impedance control helps in improving the dynamic performance of REDG units. The following paper is addresses the principle of resilient HVCS controller.

B. Resilient HVCS for three-phase GTVSG

Along with the control of AAPL and ARPL, conventional HVCS control is discussed in the aforementioned sections to compensate for fixed angular frequency harmonics in the micro-grid system. As illustrated in (11) and (12), an adjustment in resonant controllers bandwidth (ω_b) enhances the tracking error of REDG voltage and current in a closed-loop system in accordance with deviation in angular grid frequency. Whenever there is a variation in the fundamental frequency component of the micro-grid a proportional change is also observed in the respective higher-order harmonics. So, a better approach to the inherent problem is to have wider bandwidth resonant controllers. But, these former resonant controllers might cause a coupling effect between themselves thereby unpleasantly disturbing the REDG system stability.

A literature survey provides evidence of proposed adaptive controllers for accurate tracking of current under adverse frequency conditions [23]. However, the former controllers have applications in grid-tied inverters that are being operated in CCM mode, where the instantaneous angular frequency information is obtained from the existing PLL. As HVCS is a PLL-less control, the implementation of supplementary PLLs rises the REDG control complexity. Additionally, the micro-grid angular frequency information is obtained from the AAPL control scheme as mentioned in (13). Now, to provide the controllable active power required by the micro-grid, the voltage and frequency of both the REDG and grid must be synchronized. Considering the above equation into account the reference angular frequency ω_{DG} is directly acquired to design adaptive resonant controllers. The updated voltage and current control branches are

$$G_{vol}(s) = \frac{2K_{if}\omega_b s}{s^2+2\omega_b s+(\omega_{DG})^2} \quad (15)$$

$$G_{cur}(s) = k_p + \sum_{h=3,5,7,9} \frac{2K_{ih}\omega_b s}{s^2+2\omega_b s+(h\omega_{DG})^2} \quad (16)$$

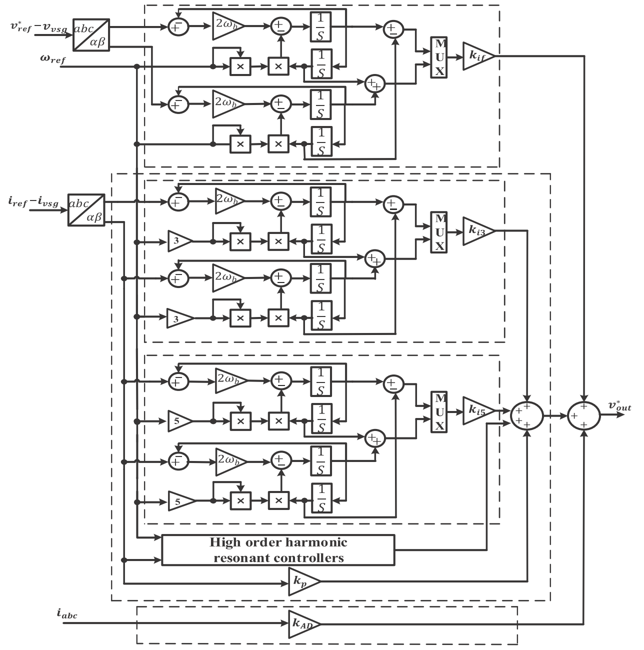

Fig. 2. Employment of angular frequency resilient HCM using DSOGI in the three-phase GTVSG system.

This paper proposes a resonant controller using the concept of the dual second-order generalized integrator (DSOGI) for three-phase systems, offering advantages over SOGI in single-phase implementation. An adaptive HVCS using DSOGI is implemented and illustrated in Fig. 2. As illustrated in (13) the reference angular frequency ω_{DG} comprehends the frequency adaptive capability of HVCS.

C. Curtailment in the complexity of the controller.

An amendment of AAPL and ARPL as illustrated in (13) and (14) along with adaptive HVCS control in (15) and (16), the control scheme of the REDG-IPECs will be minimally sensitive to variation in micro-grid frequency. The following section depicts a modified version of the control scheme by nullifying the effect of some high-/low-pass filters in the GTVSG's virtual impedance and power control loops.

To begin with, the voltage reference v_{ref}^* perceived from the GTVSG's power control loop and the HVCS voltage control branch, apprehends the fundamental angular frequency resonant controller mechanism, controls virtual impedance loop. Thus, an automatic filtration of ripples present in the voltage reference v_{ref}^* is obtained using $G_{vol}(s)$. Hence, the above-mentioned feature helps in practically removing the low-pass filter from the ARPL control scheme and from the virtual impedance loop. So, the $H_{LF}(S) = 1$ and $H_f(s) = 1$ in (14) and virtual impedance control loop respectively.

Furthermore, the harmonic current tracking using resilient HVCS in a closed-loop system is maintained by suppressing the ripples of reference angular frequency ω in (15) and (16). Therefore, the introduction of a low-pass filter is important for the AAPL control (13). So, a simplified GTVSG's power control loop and virtual impedance loop discarding low-pass/bandpass filters specifically made effective for the REDG being operated in local harmonic compensation mode and REDG harmonic rejection mode. When conventional VCM (harmonic uncontrolled mode) comes into play the input to the current control branch is set to $V_{ref}^* - V_{vsg}$. The harmonic resonant controllers present in the current control branch help in regulating the ripples in V_{ref}^*. Now to comprehend the REDG voltage V_C can significantly have huge distortions if V_{ref}^* is distorted. The former limitation can be overcome by revising the input of the current control branch in VCM mode. Considering the harmonic uncontrolled mode, the reduction in voltage distortions of the filter capacitor is the much-needed control objective thereby simply setting the input of the current controlled branch to $0 - V_C$. The applied rectification demolishes the low-pass filter $H_{LF}(s)$ in (14) and the fundamental component extraction $H_f(s)$ in the virtual impedance loop when the HVCS-based REDG unit is operated in harmonic uncontrolled mode.

At last, when HVCS-based REDG units are functioning to mitigate harmonics in local load it becomes difficult to directly control the PCC voltage quality in a micro-grid system. For example, both the shunt capacitor banks and inductive grid feeder interacting with the micro-grid system at PCC causes unexpected distortions in the PCC voltage even though the local load harmonic current is compensated by the REDG unit. The above issue can be addressed with a resistive-active power filter (R-APF) technique which is also comprehended by using the proposed RHVCS for the GTVSG system. The former one is PCC harmonic voltage $V_{PCC,h}$ can be formulated as

$$V_{PCC,h} = H_H(s).V_{PCC} \quad (17)$$

where, V_{PCC} is the PCC voltage and $H_H(s)$ is the harmonic component extractor with a bandwidth of ω_E. The expression for harmonic component extractor $H_H(s)$ can be described as

$$H_H(s) = \frac{s^2+\omega^2}{s^2+2\omega_E s+\omega^2} \quad (18)$$

According to the knowledge of PCC harmonic voltages, the HVCS reference current calculated as

$$I_{ref} = \frac{-V_{PCC,h}}{R_V} \quad (19)$$

where, the coefficient R_V regulates the reference current in the HVCS. As per (19), the REDG unit practically works as a damping resistor at specific harmonic frequencies. Fig. 3. describes an improved RHVCS control diagram. The former is also composed of three control loops within, where the modified AAPL involves a PI regulator as mentioned in (13), which is adapted to maintain accurately the active power control when variation in micro-grid frequency occurs. Furthermore, a simplified control technique is adopted with the removal of a low-pass filter in the virtual impedance loop and bandpass filters in the ARPL control mechanism. Substantially for a three-phase system, a set of adaptive DSOGI-based resonant controllers are adopted to form HVCS. To conclude the proposed RHVCS technique provides an added advantage of PCC harmonic voltage compensation capability to the REDG units. The highlights of the RHVCS illustrated in Fig. 3 can be

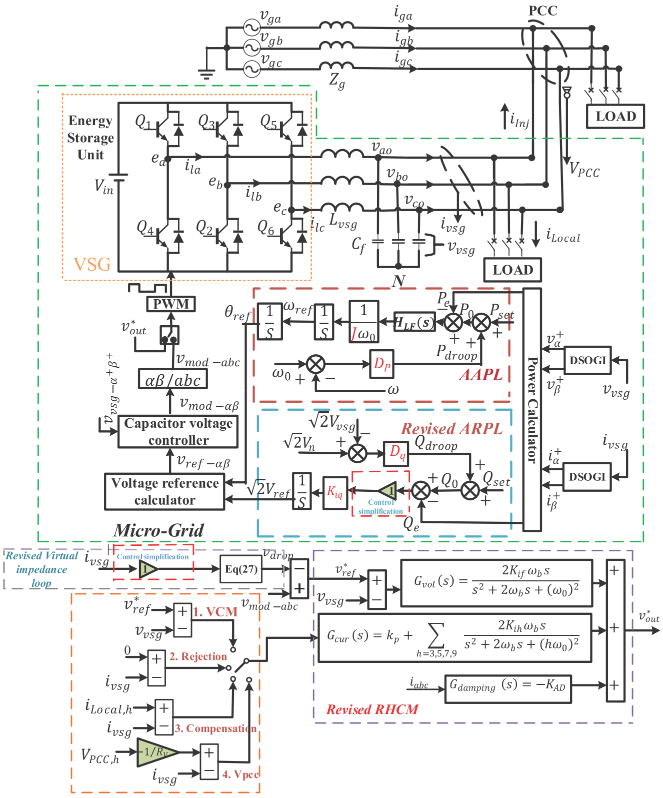

Fig. 3. Revised RHVCS for GTVSG system.

distinctively identified from the conventional HVCS shown in Fig. 1.

IV. Experimental Results

The GTVSG system along with AAPL and ARPL in the power control loop and RHVCS control for harmonic compensation was simulated in MATLAB/Simulink platform. Table I represents the parameters considered for the formulation of the proposed model and carrying out the performance analysis of GTVSG system under various conditions.

TABLE I:- GTVSG system parameters

Required Parameters	Value
Grid Voltage u_{gabc}	230 V rms
DC BUS Voltage U_{dc}	700 V
Grid frequency f	50 Hz
Switching frequency f_s	16 kHz
Grid-side inductor L_g	3 mH
Inverter-side inductor L_{vsg}	1.5 mH
Capacitor C_f	$12\mu F$
Regulator coefficient K_{iq}	0
Droop coefficient D_q	1/550
Damping Coefficient D_p	1/3450
Virtual inertia J	0.057 Kg.m^2
ω_{LF}	35 rad/s
L_{vf} and R_{vf}	3.5 mH and 0.1Ω
K_{if}	700
k_p	2.4
K_{ih}	500(h=3,5,7); 300(h=9)
ω_b	2rad/s
k_{AD}	-20
ω_E	62.8 rad/s

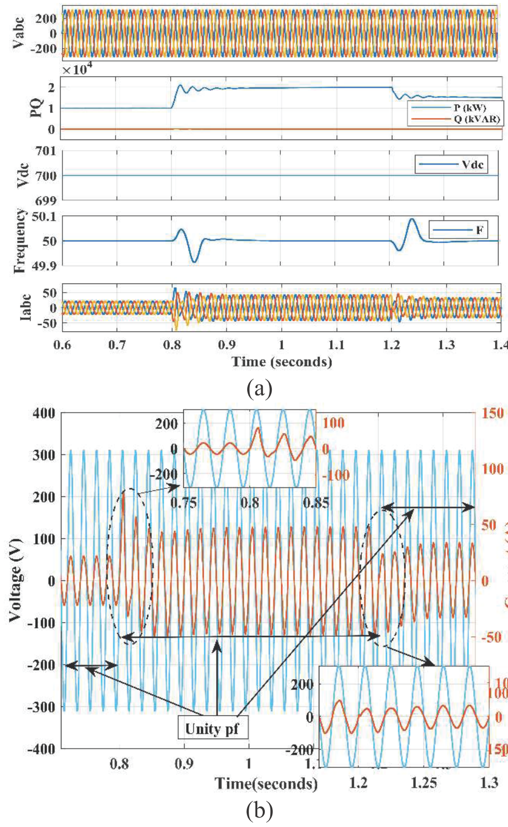

Fig. 4 Performance analysis of GTVSG (a) Change in active power (b) Power factor during Load change

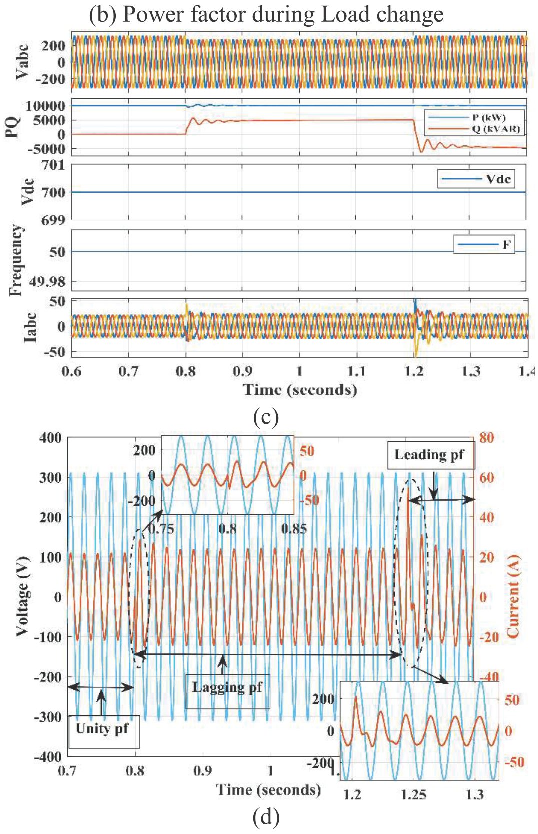

Fig. 5 Performance analysis of GTVSG (a) Change in reactive power (b) Power factor during Load change

The performance analysis of GTVSG with variation in load corresponding to change in active and reactive power and their respective power factor curves have been presented in Fig. 4 and Fig.5 respectively. The effectiveness of the control scheme is represented by PCC harmonic voltage

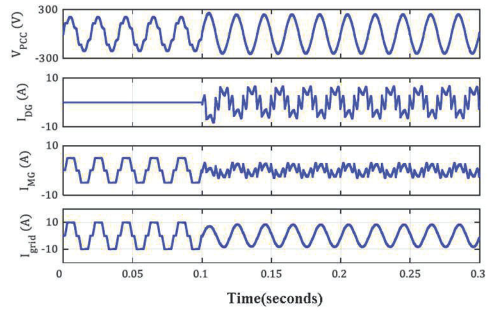

Fig. 6 PCC harmonic voltage compensation

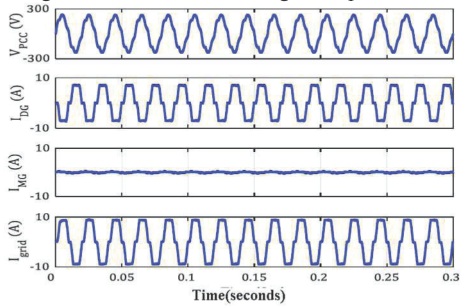

Fig. 7 Local load harmonic compensation

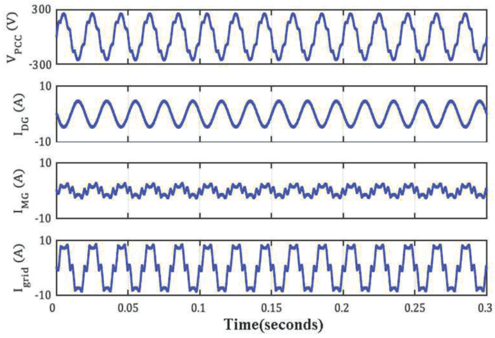

Fig. 8 REDG line current harmonic rejection

compensation in Fig. 6, local load harmonic compensation in Fig. 7 and REDG line current harmonic rejection in Fig. 8.

V. CONCLUSION

The proposed RHVCS control in the corresponding article helps in enhancing the REDG steady-state power control accuracy under adverse frequency deviations. It also helps in providing superior harmonic compensation performance and improves the power quality of the GTVSG system under variable dynamic conditions prevailing in the system.

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