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Power Hardware In The Loop Realization, Control and Simulation of Synchronous Generator Using Three Phase VSI for Microgrid Studies

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Abstract. In subject of hardware in the loop (HIL) and power hardware in the loop (PHIL) systems, a part of system is a real physical subsystem and another subsystem is simulated in the processor.

This paper discusses this concept for a synchronous generator and chooses the best options for different parts of software side for its PHIL implementation. The PHIL system is simulated in Matlab/Simulink environment and results are validated using Matlab synchronous generator block as reference system. Also, different disturbances are applied to reference and simulated systems and the results are compared. The results show synchronous generator internal and external variables are emulated correctly by realized PHIL.

Key words

PHIL, Synchronous generator, VBR model, Voltage sourced inverter, Amplifiers controller

1. Introduction

Due to need for investigating different phenomenon of synchronous generators, various tests should be conducted on it. Using a real synchronous generator in this situation is not only very costly, but also it requires big Labs and special equipments, like prime mover, cooling system, excitation system and also protection devices.

Another solution of this problem and also other similar ones comes across to the hardware in the loop (HIL) concept. The HIL is used in different areas specially in power electronics systems, and it is divided into two main categories [1]:

- Control hardware in the loop (CHIL)
- Power hardware in the loop (PHIL)

The CHIL is referred to the interaction of a hardware and a software which very low power signals are transmitted between them, but PHIL is accompanied with amplified signals which are generated by software and feeding them to hardware under test (HUT.

The HIL uses an in software running model (ISRM) to transfer signals with HUT. It means that HIL has two main parts in CHIL and three in PHIL. ISRM and HUT are two common main parts and signal amplifier is third part used in PHIL [2].

ISRM which eliminates the hardware need for a costly and complicated system like synchronous generator, is mainly using a microcontroller to receive inputs from HUT output ports and solve system equations and generate output signals in real time. As an example consider a case of PHIL, in which a real 3kW load is fed by a synchronous generator. In this case the synchronous generator equations are the ISRM, closed loop controlled voltage sourced converter (VSC) is the amplifier and the load is the HUT.

In [3], nonlinear loads in PHIL case, has been presented. The ISRM is in a digital signal processor, its amplifier is a voltage sourced inverter and HUT is also an inverter.

In [4], another case of PHIL with nonlinear load has been presented. [5] has used a system of converters with the capability of regeneration, to develop a PHIL implementation of wind power generation and consumption substation. A combined power system distributed generation resources have been emulated in [6], using two voltage sourced converters as amplifier and a digital signal processor to model the ISRM. A diesel generator has been emulated and presented in [7] that its ISRM just includes stator and field windings, and other features have not been included.

The HIL testing has important advantages such as preventing testing damages, reducing cost of test and ease of implementation compared to fully real hardware test.

The aim of this paper is to realize a PHIL model for emulating synchronous generators using VSCs, to use in microgrid studies. Main parts in a PHIL system are determined and applied to this specific issue. A full order and computationally optimized model is used for synchronous generator which is implemented in an embedded function block in Matlab/Simulink, playing the role of a microcontroller. A VSC is used as amplifier and modelled and controlled in Simulink environment. A fully analytical procedure is used to decuple and control amplifier parts multi-input multi-output (MIMO) system. Then, connecting these two parts to each other (synchronous generator embedded block providing inverter closed loop signals) make the synchronous generator emulator, and a HUT (like a three phase resistive load) connected to it, forms the power system. The load in the future will be replaced with a microgrid to study different phenomenon in microgrid. Such a work has been done in [8]. This microgrid is shown in Fig.1 .The designed synchronous generator emulator is validated using Matlab/Simulink synchronous generator block as a reference model, by applying disturbances to it and simulated PHIL, and comparing the results.

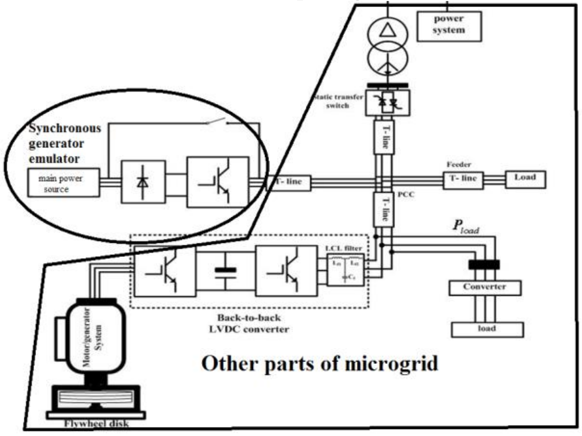

Fig. 1:Synchronous generator emulator position in future microgrid

2. Model Realization

For modelling synchronous generator emulator, realizing before mentioned three parts and depicted in fig.2, is essential.

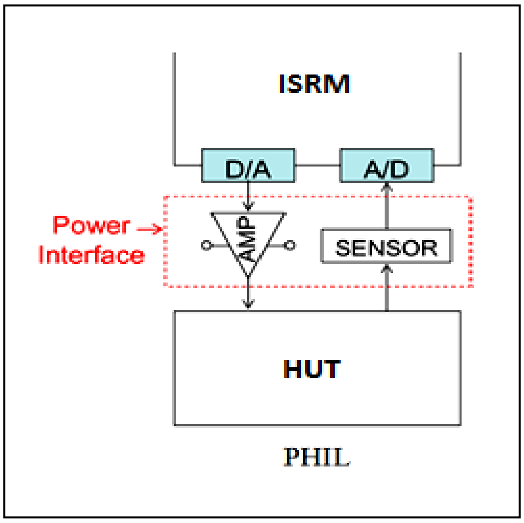

Fig.2: Typical PHIL system main parts

The HUT is a 3kW and three phase real load. The amplifier is a closed loop controlled three phase inverter which its reference is output signals of digital to analogue converter obtained from digitally solved ISRM.The ISRM is a nonlinear set of equations which are referred to voltage behind reactance (VBR) model for synchronous generator. Fig. 3 shows modelling details.

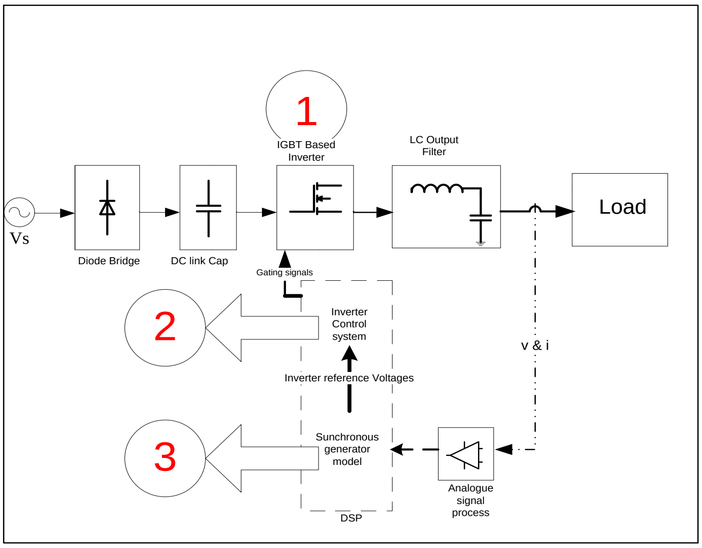

Fig.3 :detailed diagram of synchronous generator emulator

As can be seen in this figure, main power is utilized for feeding the PHIL amplifier, voltage sourced converter, and the filter is placed between inverter (amplifier) and the load (HUT) to mitigate switching harmonics of controlled output voltage.

First part codes in DSP(numbered by 3 in fig.3), which will be modelled as Matlab embedded function, is related to mentioned VBR model (see section 3).

The region which is numbered by 2, is also related to amplifier. This is digital implementation of closed loop control algorithm for inverter which will be discussed in detail in section 4.

Section 5 simulates and validates the PHIL implementation for synchronous generator using Matlab synchronous generator block.

3. VBR Model

This model of synchronous generator is a full order model, which is proved to be suitable for digital implementation rather than other models like *dq* model, state space model and transfer function model.

Its main feature is instantaneously solving of stator and rotor equations, despite traditional *dq* model.

The VBR model is based on synchronous generator equations in the form of (1)[9].

$$\boldsymbol{V}_{abcs} = -\boldsymbol{r}_s \boldsymbol{i}_{abcs} + \boldsymbol{p}\left[\boldsymbol{L}''_{abcs}(\boldsymbol{\theta}_r)\boldsymbol{i}_{abcs}\right] + \boldsymbol{V}''_{abcs} \qquad (1)$$

Where, $\boldsymbol{L}''_{abcs}(\boldsymbol{\theta}_r)$ is subtransient inductance matrix given in (2) and $\boldsymbol{V}''_{abcs}$ is voltage matrixes subtransient term presented by (3).

$$L''_{abcs}(\theta_r) = \begin{bmatrix} L_S(2\theta_r) & L_M\left(2\theta_r - \frac{2\pi}{3}\right) & L_M\left(2\theta_r + \frac{2\pi}{3}\right) \\ L_M\left(2\theta_r - \frac{2\pi}{3}\right) & L_S\left(2\theta_r - \frac{4\pi}{3}\right) & L_M(2\theta_r) \\ L_M\left(2\theta_r + \frac{2\pi}{3}\right) & L_M(2\theta_r) & L_S\left(2\theta_r + \frac{4\pi}{3}\right) \end{bmatrix} \qquad (2)$$

L_M and L_S are functions of machine constants and rotor position.

$$\boldsymbol{V}''_{abcs} = \left[\boldsymbol{K}_s(\boldsymbol{\theta}_r)\right]^{-1}\left[\boldsymbol{V}''_q \;\; \boldsymbol{V}''_d \;\; \boldsymbol{0}\right]^T \qquad (3)$$

In (3), K_s is park transformation matrix, and $\boldsymbol{V''_{qd}}$ is *q* and *d* axis subtransient voltages. This voltages are obtained from (4).

$$V''_q = \omega_r \lambda''_d + \frac{L''_{mq} r_{kq1}\left(\lambda''_q - \lambda_{kq1}\right)}{L^2_{lkq1}} + \frac{L''_{mq} r_{kq2}\left(\lambda''_q - \lambda_{kq2}\right)}{L^2_{lkq2}} + \left(\frac{r_{kq1}}{L^2_{lkq1}} + \frac{r_{kq2}}{L^2_{lkq2}}\right) L''_{mq} i_{qs}$$

$$V''_d = -\omega_r \lambda''_q + \frac{L''_{md} r_{kd}\left(\lambda''_d - \lambda_{kd}\right)}{L^2_{lkd}} + \frac{L''_{md}}{L_{lfd}} v_{fd} + \frac{L''_{md} r_{fd}\left(\lambda''_d - \lambda_{fd}\right)}{L^2_{lfd}} + \left(\frac{r_{kd}}{L^2_{lkd}} + \frac{r_{fd}}{L^2_{lfd}}\right) L''_{md} i_{ds}$$

$$\lambda''_q = L''_{mq} \frac{\lambda_{kq1}}{L_{lkq1}} + L''_{mq} \frac{\lambda_{kq2}}{L_{lkq2}}$$

$$\lambda''_d = L''_{md} \frac{\lambda_{kd}}{L_{lkd}} + L''_{mq} \frac{\lambda_{fd}}{L_{lfd}} \qquad (4)$$

The rotor equations are as follows:

$$p\lambda_j = -\frac{r_j}{L_{lj}}\left(\lambda_j - \lambda_{mq}\right) \qquad j = kq1, kq2$$

$$p\lambda_j = -\frac{r_j}{L_{lj}}\left(\lambda_j - \lambda_{md}\right) + v_j \qquad j = fd, kd$$

$$\lambda_{mq} = L''_{mq}\left(\frac{\lambda_{kq1}}{L_{lkq1}} + \frac{\lambda_{kq2}}{L_{lkq2}} + i_{qs}\right)$$

$$\lambda_{md} = L''_{md}\left(\frac{\lambda_{fd}}{L_{lfd}} + \frac{\lambda_{kd}}{L_{lkd}} + i_{ds}\right) \qquad (5).$$

The mechanical equations of the VBR model is presented by (6).

$$p\theta_r = \omega_r$$

$$p\omega_r = \frac{P}{2J}\left(T_e - T_m\right)$$

$$T_e = \frac{3P}{4}\left(\lambda_{md} i_{qs} - \lambda_{mq} i_{ds}\right) \qquad (6).$$

In all above equations λ ,L and r are stand for flux, inductance and resistance, respectively.

The main advantage of VBR model is possibility of direct interface of synchronous generator to the external grid in contrast to traditional models like *dq* model, and it uses advantages of solving equations in *d-q* coordinate simultaneously.

The stator equation can be considered as two separate sets, the first one is in *abc* frame and does not need any transformation, and second one is a transformation of subtransient voltages equations solved in *d-q* coordinate. Note that rotor equation are linear first order differential equations and will be solved in state space form.

4. PHIL amplifier and Its control

A voltage sourced two level three phase inverter is dedicated to voltage amplification and power generation in synchronous generator emulator PHIL system. Since synchronous generator will be considered as frequency dictator in the grid and it is assumed that there is no other generator, then this inverter, as PHIL amplifier, will be a standalone inverter which should determine frequency.

On the other hand, the output voltage of the inverter is the generators emulator output voltage, leading to inverter output voltage control necessity. Then the inverter voltage and frequency should be controlled. Fig.4 shows the inverter and its main feedback, transformation and control signals [10].

As it is evident from Fig.4, the core of the control system is a current control loop and the outer voltage loop is used for main control variable.

First of all, it is important to understand inner current control loop. Writing core system equations in *abc* frame and then transforming them into *d-q* frame leads to Equations (7) and (8) for the current controlled system.

$$L\frac{di_d}{dt} = L\omega_0 i_q - \left(R + r_{on}\right) i_d + V_{td} - V_{sd} \qquad \textbf{(7)}$$

$$L\frac{di_q}{dt} = -L\omega_0 i_d - \left(R + r_{on}\right) i_q + V_{tq} - V_{sq} \qquad \textbf{(8)}$$

This equations present a coupled MIMO system.

Subtracting $L\omega_0 i_q$ from *d* axis controller output and a adding $L\omega_0 i_d$ to the *q* axis controller output decouple the MIMO system to the two linear and totally similar SISO systems. This method is called feedforward decoupling. Then i_{dref} and i_{qref} control i_d and i_q, respectively. This system is shown in fig.5.

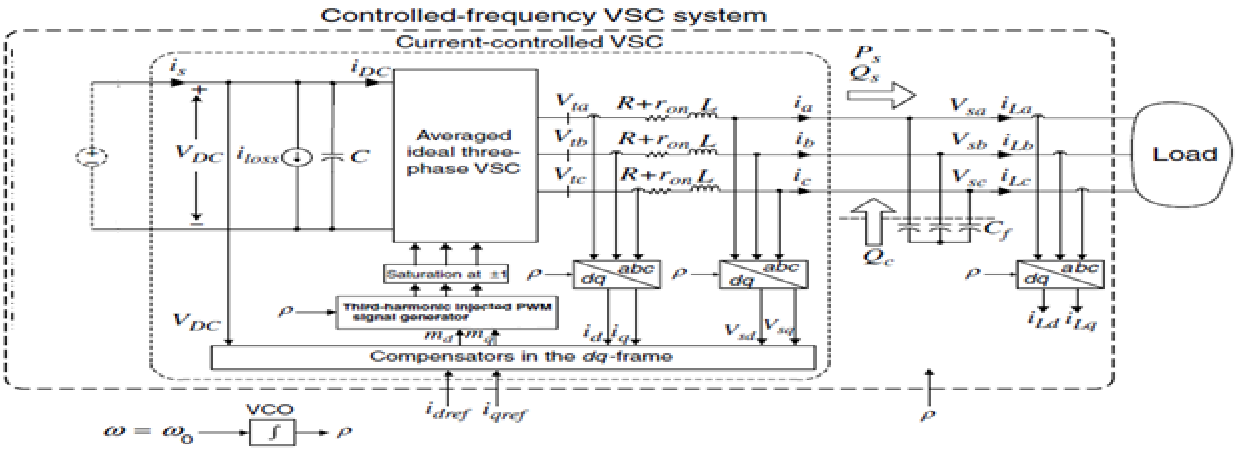

Fig.4: PHIL system amplifiers main structure

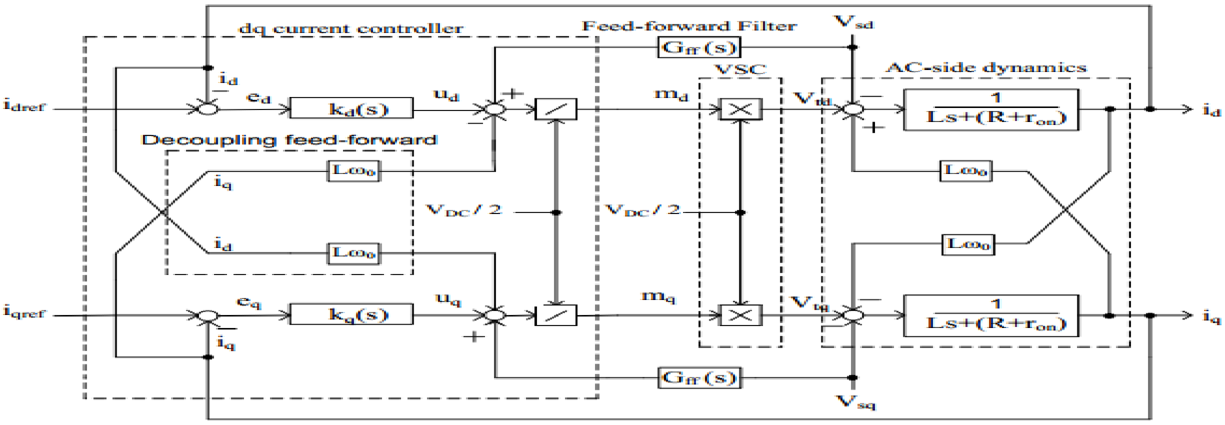

Fig.5: Closed loop current control schem

$K_d(s)$ and $K_q(s)$ are PI controllers. It is easy to conclude that setting K_p and K_i to $\frac{L}{\tau_i}$ and $\frac{(R+r_{on})}{\tau_i}$, respectively , results in fig.6 (the simplified form of fig.5) and equation (9).

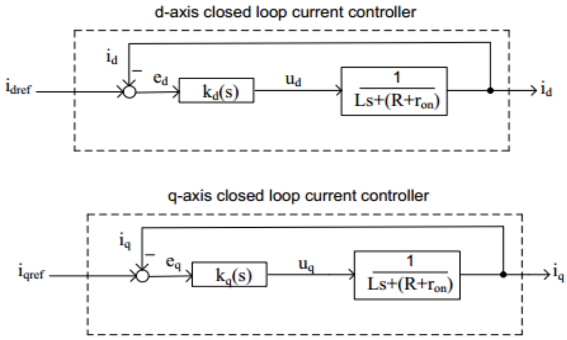

Fig.6: Simplified block diagram of current control loop

$$\frac{I_d}{I_{dref}}=\frac{I_{dq}}{I_{qref}}=G_i(s)=\frac{1}{\tau_i s+1} \qquad (9)$$

By adding capacitor to the system output, the following equation can show the relation among load current (i_L), current controlled system current (i) and output voltage (V).

$$C_f\frac{dV_{sa}}{dt}=i_a-i_{La},C_f\frac{dV_{sb}}{dt}=i_b-i_{Lb},C_f\frac{dV_{sc}}{dt}=i_c-i_{Lc}$$
(10)

Appling *d-q* transformation to (10) leads to (11) and (12), which are similar to (7) and (8) in terms of coupling and constructing MIMO system. This is also shown in fig.7.

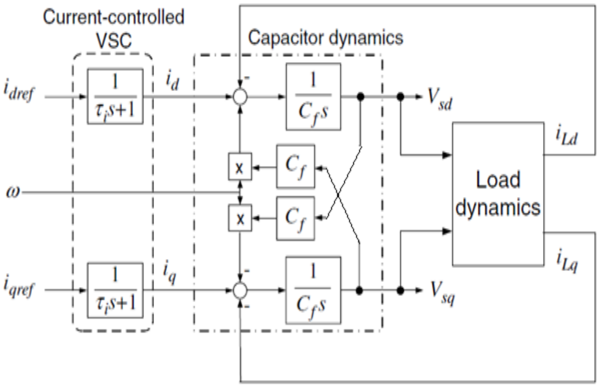

Fig.7: Coupling between *d* and *q* axises in voltage loops

$$C_f\frac{dV_{sd}}{dt}=C_f(\omega V_{sq})+i_d-i_{Ld} \qquad (11)$$

$$C_f\frac{dV_{sq}}{dt}=-C_f(\omega V_{sd})+i_q-i_{Lq} \qquad (12)$$

The same as the current control loop, a feed forward decoupling method is used for decoupling *d* and *q* axis voltage control, and a part of load current is added to the current reference to make the load dynamic independent of the voltage control system. This final control system is shown in fig.8. It is worth noting that decoupling is not completely achieved with this method and writing fig.8 equations clarifies condition for fully decoupling of axises [9]..

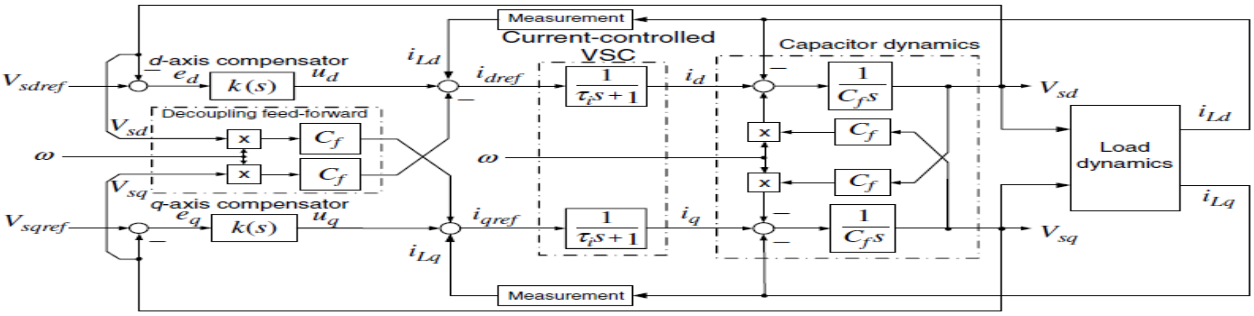

Fig.8: Complete and detailed control block diagram of voltage controlled inverter

Designing controllers for voltage loops, is based on simplified fig.8, with assumption of small enough τ_i resulting in $G_i(s)$ unit dc gain, and making fully decoupled *d* and *q* systems.

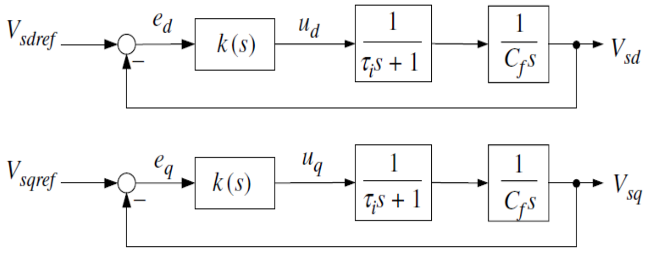

Fig.9 :Simplified and decoupled diagram of whole voltage control system

The PI controllers with loop shaping are designed for voltage loop in fig.9 and a 53 degree phase margin can be achieved for the closed loop system.

5. Simulations and Validation

In this section, the VBR model is coded in an embedded function block in Simulink environment. The VBR equations are discretized using trapezoidal rule.

The parameters of 3.7 kW and 4 pole synchronous generator are summarized in Table I and used in simulations.

Table I: Synchronous generator parameters

$r_s = 382m\Omega$	$L_{mq} = 24.9mH$
$L_{ls} = 1.12mH$	$L_{md} = 39.3mH$
$r_{kd} = 1.58\Omega$	$L_{lkd} = 4.52mH$
$r_{kq1} = 447m\Omega$	$L_{lkq1} = 4.21mH$
$r_{kq2} = 1.06\Omega$	$L_{lkq2} = 3.5mH$
$r_{fd} = 112m\Omega$	$L_{lfd} = 1.53mH$

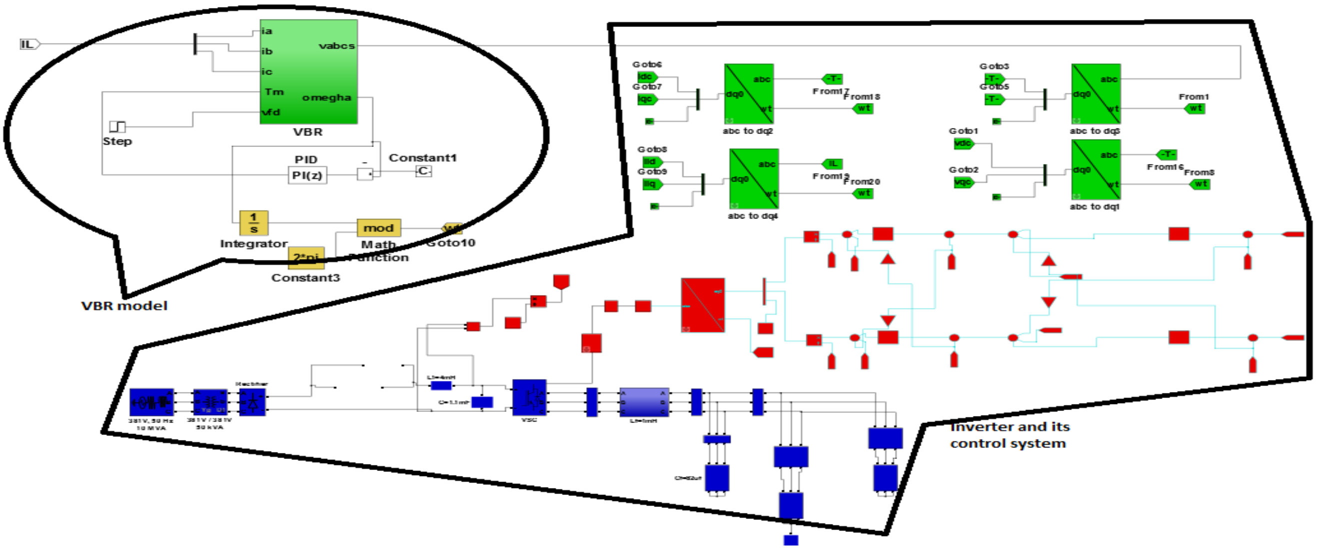

Fig.10:Synchronous generator simulink PHIL implementation

The complete system PHIL implementation in Matlab/Simulink is shown in fig.10.

The left side in fig.10 is named the VBR model, which consists of the VBR model embedded function and a speed control loop which simulates the microcontroller.

The right side of this figure has three parts shown in blue, red and green. The green part is *d-q* and *q-d* transformations. The red part is the inverter control section, and blue part is the inverter (PHIL amplifier) and load (HUT).

In the first simulated scenario, there are two disturbances at t=4s and t=7s, respectively.

First disturbance is a field voltage 0.3pu increase, and the second one is load resistance decrease to half of its value.

Fig.11 shows the electrical speed deviation due to these disturbances.

The load angle of generator is also compared in fig.12, for Simulink PHIL implementation, and Matlab synchronous generator block. At t=4s, following to filed voltage increase, the load angle has no change, approximately, in both reference and introduced system. At t=7s, when the load resistance decreases and its power goes up for constant voltage, the load angles increases, which is reasonable.

The electrical torque, is compared in fig.13. It is observable that electrical torque has been increased in response to field voltage increase, and it exactly follows the reference system.

The voltage waveform is also coinciding in the output of reference and PHIL Simulink implementation. This is shown in fig.13 at t=7s.

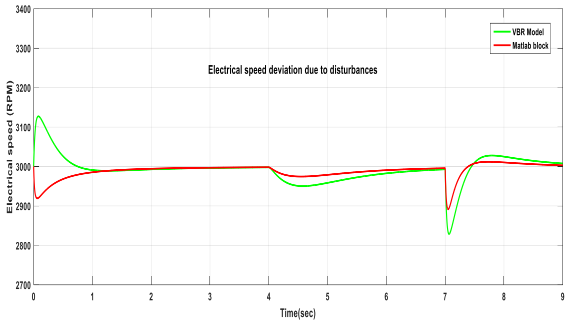

Fig.11: **Electrical speed deviation due to disturbances in reference and actual system**

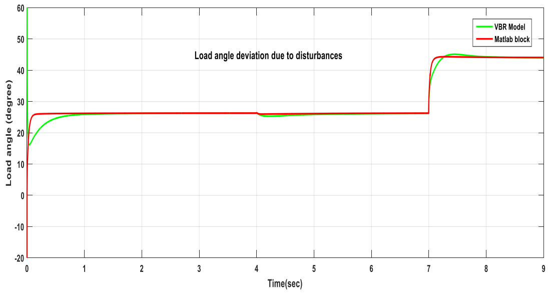

Fig.12: **Load angle deviation due to disturbances in reference and actual system**

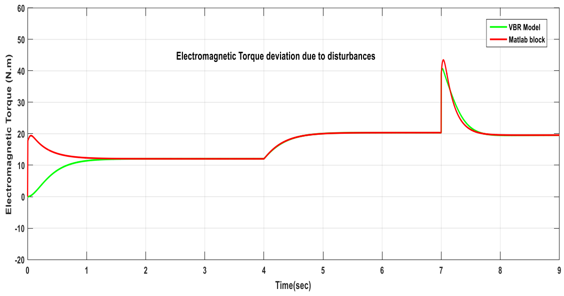

Fig.13: **Electrical torque deviation due to disturbances in reference and actual system**

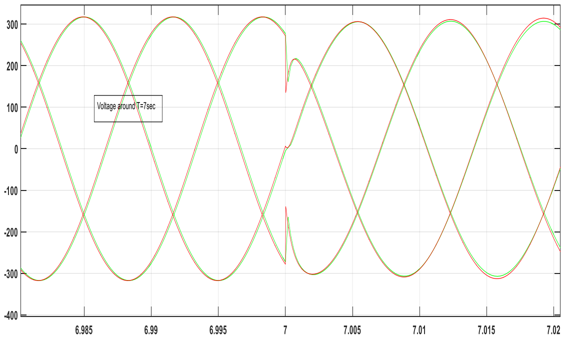

Fig.14: **Phase A voltage consistency during to disturbance in reference and actual system**

6. Conclusion

In this paper, different parts of a PHIL system have been introduced and applied to synchronous generator. These different parts, including ISRM (in software running model), amplifier and its controller, and HUT (hardware under test) have been theoretically analysed and chosen for simulations. The whole PHIL system has been simulated in Matlab/Simulink and results have been validated using Matlab synchronous generator block showing this method containing specified elements is the most proper method to implement synchronous generator emulator.

References

[1] W. Ren, M. Steurer, and T. L. Baldwin, "Improve the Stability and the Accuracy of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithms," *IEEE Transactions on Industry Applications,* vol. 44, pp. 1286-1294, 2008.

[2] B. Lu, X. Wu, H. Figueroa, and A. Monti, "A Low-Cost Real-Time Hardware-in-the-Loop Testing Approach of Power Electronics Controls," *IEEE Transactions on Industrial Electronics,* vol. 54, pp. 919-931, 2007.

[3] Y. S. Rao and M. C. Chandorkar, "Real-Time Electrical Load Emulator Using Optimal Feedback Control Technique," *IEEE Transactions on Industrial Electronics*, vol. 57, pp. 1217-1.2010,225

[4] M. Kesler, E. Ozdemir,and M. C. Kisacikoglu "Power Converter-Based Three-Phase Nonlinear Load Emulator for a Hardware Testbed System," *IEEE Transactions on Power Electronics*, vol. 29, pp. 5806-5812, 2014.

[5] Y. Ma, L. Yang, J. Wang, F. Wang, and L. M. Tolbert, "Emulating full-converter wind turbine by a single converter in a multiple converter based emulation system," in 2014 IEEE Applied Power Electronics Conference and Exposition - APEC 2014, 2014, pp.3047-3042.

[6] X. R. I. Andrew, M. Anand, and P.Sivakumar ,"Modelling and analysis of emulator for distributed generation sourced smart grid using digital signal controller (TMS320F28335)," in Innovative Smart Grid Technologies - India (ISGT India), 2011 IEEE PES, 2011, pp. 160-166.

[7] M. Torres and L. A. C. Lopes, "Inverter-based virtual diesel generator for laboratory-scale applications," in *IECON 2010 - 36th Annual Conference on IEEE Industrial Electronics Society*, 2010, pp. 532-537.

[8] M.Ssnjary, G.B.Gharehpetian , "Game Theoretic Approach to Cooperative Control of Distributed Energy Resources in Islanded Microgrid Considering Voltage and Frequency Stability" , NEURAL COMPUTING & APPLICATIONS , Vol.25 , NO.2 , PP.343 _ 351 , 01 August2014

[9] L. Wang and J. Jatskevich, "A Voltage-Behind-Reactance Synchronous Machine Model for the EMTP-Type Solution," in *Power Engineering Society General Meeting, 2007. IEEE*, 2007, pp. 1-1.

[10] R. I. Amirnaser Yazdani, *Voltage-Sourced Converters in Power Systems : Modeling, Control, and Applications*: Wiley 2010.