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# Implementation and design non-linear controller for stand-alone generator

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**ABSTRACT**

This article describes the implementation and design of a non-linear controller for a stand-alone generator which has a DC motor as a prime mover based on input-output feedback linearization (FL) technique. While in the grids-connected synchronous generator the attention is focused on the load angle as stability assessment, the speed and terminal voltage is the main effective state in stand-alone generators. Therefore, the FL robust control design method is utilized to truck the desired speed and terminal voltage. First, a non-linear mathematical model is derived for the synchronous generator with a dc motor as a prime mover then input-output FL is applied to this non-linear model to make it linear. The tracking control low of the linearized model is designed using a pole placement technique. For verifying the efficiency and performance of the system, several tests were conducted in the Matlab simulation with some experimental results. These results showed a high dynamic response to a large and fast load difference and zero steady-condition error.

**Keywords**: back-emf, brushless machines, sensorless operation, phase advance, permanent magnet, pulse width modulation.

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## 1. Introduction

Extensive urbanization has led to an increased need to produce electricity from renewable sources such as wind and solar energy system. This has been accompanied by the increasing emergence of stand-alone generators to feed isolated load or to optimize the use of renewable energy. One of the specific applications of a stand-alone generator is when a power outage occurs [1][2] [3]. This situation should be avoided to prevent financial losses to electricity suppliers and essential consumers. In this work, the stand-alone synchronous generator with a DC motor as a prime mover is studied. This system is potentially various from the grids-connected topology. While the interest in the first system is in terms of fixed frequency and voltage, the interest in grids-connected generator depends on the load angle as a pointer for stability. Besides, nature damping of the system must be with acceptable limits [4][5]. The potential contribution of this work is the single robust non-linear controller use for a motor-generator set which mostly depends on the renewable energy source. This work presents a non-linear feedback input-output linearization controller for motor-generator set. The approach of FL has been utilized previously in several areas of control to address the performance problems of non-linear control system include the control of helicopters, high-performance aircraft and enduring magnet synchronous generator in the wind energy system. In its simplest form, input-output linearization amount to cancelling the nonlinearities in a non-linear system to the closed-loop dynamic is in a linear procedure [6][7]. The central principle of this method depends on the algebraic translation of the non-linear structure into an entirely or partially linear system to implement the linear controlling method. This is completely different from classical linearization (for example Jacobean linearization) include that FL is done by precise conversion and input of the state but instead by linear approximation of the dynamic method based on the particular operational point.

### 1.1. The Depiction of the system

Figure 1 displays the system's graphical representation. As a mover prime, the seldom-used DC motor drags a synchronous motor to fill an independent load. M is the mechanical velocity, Vs, Vf and Va is the voltage of the stator, field and armature. $I_{f,}$ and ia are the current of the stator, field and armature respectively [8-9].

As mentioned above, this system is various from the characteristic grids-connected generator in which the speed of DC motor is responsible for determining the frequency of the system, while the excitation voltage must assure the voltage amplitude. Also, in this figure, the voltage supplied to armature and field excitation is taken from the separated dc voltage source through DC/DC chopper [10].

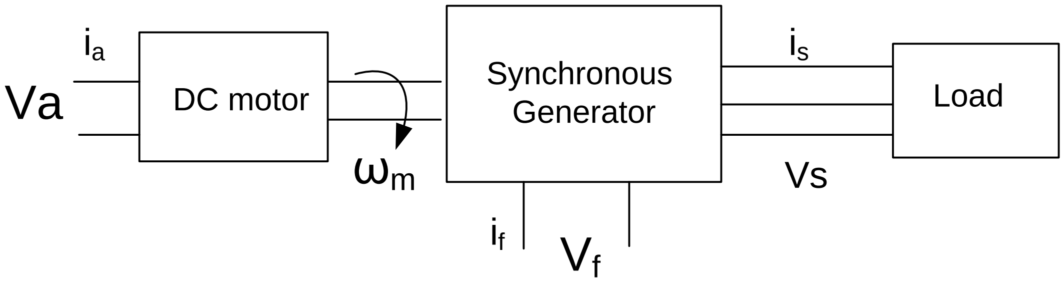


Figure 1. system description

### 2.1. System modeling

#### 2.1.1. DC motor

Despite the frequent study of the mathematical model of DC motors by researchers, it is useful to refer to the basic differential equations that were governing the behaviour of the separately excited DC motor [9]. The state equations are:

$$\frac{di_a}{dt} = \frac{1}{La}[v_a - K_b\omega_r - R_a i_a] \quad \dots(1)$$

$$\frac{d\omega_r}{dt} = \frac{1}{J_1}[T_{e1} - D\omega_r - T_L] \quad \dots(2)$$

$$T_{e1} = K_t i_a \quad \dots(3)$$

Where $La$ armature inductance in henry, $v_a$ armature voltage in volt, $K_b$ =motor back emf constant volt.sec/rad, $\omega_r$ rotor speed in rad/sec, $R_a$ armature resistance in ohm, $i_a$ armature current in Ampere, $T_{e1}$ motor electromagnetic torque in N.m, $J_1$ moment of inertia, $D$ viscous coefficient, $K_t$ =torque constant of the motor N.m/amper, $T_L$ load torque in N.m, and $La$ armature inductance in henry.

#### 2.1.2. Synchronous generator

As a well known, to formulate a suitable mathematical model for the synchronous generator feeding a purely resistive load, and alteration of coordinates is essential. The theory frame reference accurately describes the mathematical steps to transfer the natural synchronous generator equation set which include time-varying coefficient to a new set of equations with a time-invariant coefficient [10][11]. We would be using the rotor reference frame and assuming a singular resistor load. The whole electrical formulas of dynamic systems are presented in d q coordinates in an affine form as:

$$L\frac{dx}{dt} = \begin{pmatrix} -R_s & \omega L_s & 0 \\ -\omega L_s & -R_s & -\omega L_m \\ 0 & 0 & -R_F \end{pmatrix} X + \begin{pmatrix} v_d \\ v_q \\ v_F \end{pmatrix} \quad \dots(4)$$

$$\boldsymbol{x} = \begin{bmatrix} \boldsymbol{i_d} \\ \boldsymbol{i_q} \\ \boldsymbol{i_F} \end{bmatrix}$$

Where $\boldsymbol{L} = \begin{bmatrix} \boldsymbol{L_s} & \boldsymbol{0} & \boldsymbol{L_m} \\ \boldsymbol{0} & \boldsymbol{L_s} & \boldsymbol{0} \\ \boldsymbol{L_m} & \boldsymbol{0} & \boldsymbol{L_F} \end{bmatrix}$

is the inductance matrix, $x^T = (i_d, i_q, i_F) \in \mathbb{R}^3$, which are the dq field and stator currents respectively, $R_F$ and Rs are the field and stator resistance. Ls, Lm, and $L_F$ are the stator, magnetizing, and field inductance. ω is the electrical speed ($\omega_e = p\omega_r$, where p is the pole pairs' number). $v_d$ and $v_q$ are the dq voltages of a stator, and $v_F$ is the voltage of that field which would be utilized as a controlling input. For designing the non-linear controller, first, we need to build a complete mathematical model for synchronous generators associated with a resistive load $R_L$. As shown in Fig 1, where $V_s^T = V_L^T = (v_{Ld}, v_{Lq}) \in \mathbb{R}^2$ and $i_L^T = (i_{Ld}, i_{Lq}) \in \mathbb{R}^2$ are the currents and load voltages in dq coordinates associated by

$$\begin{pmatrix} v_{Ld} \\ v_{Lq} \end{pmatrix} = R_L \begin{pmatrix} i_{Ld} \\ i_{Lq} \end{pmatrix}$$

According to Fig1, $V_s = V_L$

$$A = \begin{pmatrix} -(R_{s+}R_L) & \omega L_s & 0 \\ -\omega L_s & -(R_s + R_L) & -\omega L_m \\ 0 & 0 & -R_F \end{pmatrix}$$

And $B = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$

In this study we use current as a state variable

$$\frac{di_d}{dt} = -a_1 i_d + a_2 \omega_r i_q + a_3 i_F - a_4 v_F \qquad \dots(5)$$
$$\frac{di_q}{dt} = -a_5 \omega_r i_d - a_6 i_q - a_7 \omega_r i_F \qquad \dots(6)$$
$$\frac{di_F}{dt} = a_8 i_d - a_9 \omega_r i_q - a_{10} i_F + a_{11} v_F \qquad \dots(7)$$

Electrical torque $T_{e2} = \frac{3}{2}\frac{P}{2}\left[L_{md}(-i_d + i_F)i_q + L_{mq} i_q i_d\right]$

Since we assume $L_{md} = L_{mq} = L_m$

$\therefore \quad T_{e2} = \frac{3}{2}\frac{P}{2}\left[L_m\, i_F\, i_q\right] \qquad \dots(8)$

And finally, the equation of rotor speed is

$$\frac{d\omega_r}{dt} = \frac{P}{2J_2}\left[T_m - T_{e2} - T_D\right] \qquad \dots(9)$$

where $\mathrm{a_i} = \text{constant defined in appendix A}$

### 2.1.3. Mechanical coupling system for non-linear model

Because both machines spin at a similar speed, only one mathematical formulation for the rotational speed is needed for the motor-generator collection. It is apparent that the load torque of the DC engine is the synchronous machine's input (load) torque, which is derived utilizing the equations (2) and (9) [16] [17]:

$$\boldsymbol{T_{e1}} - \boldsymbol{J_1}\frac{\boldsymbol{d\omega_r}}{\boldsymbol{dt}} = \boldsymbol{T_{e2}} + \frac{\boldsymbol{2}}{\boldsymbol{P}}\boldsymbol{J_2}\frac{\boldsymbol{d\omega_r}}{\boldsymbol{dt}} \qquad \dots(10)$$

Rearrange equation (10) for the speed as a state variable we obtain
$\frac{d\omega_r}{dt} = P(T_{e1} - T_{e2})/(2J_2 + PJ_1)$ …(11)

Equations (1),(5),(6 ),(7), and (11) represent the total state space for the motor-generator set, with Output states:[ $\omega r, V_s$], and input states[ $\boldsymbol{va}, \boldsymbol{v_F}$], where $\omega_r$ rotor speed in rad/sec, $V_s$ generator terminal voltage in volt, $v_a$ motor armature voltage in volt, and $v_F$ field voltage in volt. We could write a non-linear model of the motor-generator set as:

$$\begin{bmatrix} \dot{i}_a \\ \dot{i}_d \\ \dot{i}_q \\ \dot{i}_F \\ \dot{\omega}_r \end{bmatrix} = \begin{bmatrix} \frac{-R}{L_a} & 0 & 0 & 0 & \frac{-K_b}{L_a} \\ 0 & -a_1 & a_2\omega_r & a_3 & 0 \\ 0 & -a_5\omega_r & -a_6 & -a_7\omega_r & 0 \\ 0 & a_8 & -a_9\omega_r & -a_{10} & 0 \\ kK_t & 0 & 0 & -ka_{12}i_a & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_d \\ i_q \\ i_F \\ \omega_r \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} & 0 \\ 0 & -a_4 \\ 0 & 0 \\ 0 & a_{11} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} v_a \\ v_F \end{bmatrix} \quad \ldots(12)$$

Where: $k = \frac{P}{(2J_2+PJ_1)}$ , $a_{12} = \frac{3}{2}\frac{P}{2}L_m$ , $R = R_s + R_L$

$$\boldsymbol{V_s = \sqrt{{V_d}^2 + {V_q}^2} \qquad V = {V_s}^2 = {V_d}^2 + {V_q}^2 = (R_L i_d)^2 + \left(R_L i_q\right)^2} \quad \textbf{…(13)}$$

### 2.1.4. Principle concept of output-input FL

It is useful to review the concept of state FL before design the non-linear controller to the isolated motor-generator set. A non-linear state equation for a MIMO system is:

$$\dot{\boldsymbol{x}} = \boldsymbol{f}(\boldsymbol{x}) + \boldsymbol{g}(\boldsymbol{x})\boldsymbol{u} \qquad \textbf{….(14)}$$

and the output is of that system given as

$$\boldsymbol{y} = \boldsymbol{h}(\boldsymbol{x}) \qquad \textbf{…(15)}$$

For MIMO systems, the output-input linearization process implies the emerging of at least one input by differentiating the output $y_j$ [13-15].
Consider $\mathcal{L}fh$ and $\mathcal{L}gh$ the derivatives of lie $h(x)$ with respect to $f(x)$ and$g(x)$,$\dot{y}_j$ could be inscribed as:

$$\boldsymbol{\dot{y}_j = \mathcal{L}f h_j + \textstyle\sum_{i=1}^{m}\left(\mathcal{L}g_i h_j\right) u_i} \quad \ldots(16)$$

Assuming that $y_j$ needs to differentiate $r_j$ times before at least one inputs appears, then:

$$\boldsymbol{{y_j}^{r_j} = \mathcal{L}_f^{r_j} h_j + \textstyle\sum_{i=1}^{m} \mathcal{L}_{gi}\mathcal{L}_f^{r_j-1} h_j u_i} \quad \textbf{…(17)}$$

As follows , Eqn (17) could be written into a matrix form:

$$\begin{bmatrix} \boldsymbol{y_1}^{(r_1)} \\ \vdots \\ \boldsymbol{y_m}^{(r_m)} \end{bmatrix} = \begin{bmatrix} \boldsymbol{\mathcal{L}_f^{r_1} h_1(x)} \\ \vdots \\ \boldsymbol{\mathcal{L}_f^{r_m} h_m(x)} \end{bmatrix} + \boldsymbol{E}_{(x)} \begin{bmatrix} \boldsymbol{u_1} \\ \vdots \\ \boldsymbol{u_m} \end{bmatrix} \quad \textbf{…(18)}$$

Suppose the decoupling matrix for the MIMO system is referred to as $m \times m$matrix $E(x)$. It has an expression as follows:

$$\boldsymbol{E}_{(x)} = \begin{bmatrix} \boldsymbol{\mathcal{L}_{g1}\mathcal{L}_f^{r_1-1} h_1} & \ldots & \boldsymbol{\mathcal{L}_{gm}\mathcal{L}_f^{r_1-1} h_1} \\ \vdots & \ddots & \vdots \\ \boldsymbol{\mathcal{L}_{g1}\mathcal{L}_f^{r_m-1} h_m} & \ldots & \boldsymbol{\mathcal{L}_{gm}\mathcal{L}_f^{r_m-1} h_m} \end{bmatrix} \quad ….(19)$$

The control input vector $u$ is selected as follows by linearizing Eqn (18):

$$\boldsymbol{u} = -\boldsymbol{E}^{-1}\begin{bmatrix}\mathcal{L}_f^{r_1}\boldsymbol{h_1}(\boldsymbol{x})\\ \vdots \\ \mathcal{L}_f^{r_m}\boldsymbol{h_m}(\boldsymbol{x})\end{bmatrix} + \boldsymbol{E}^{-1}\begin{bmatrix}\boldsymbol{v_1}\\ \vdots \\ \boldsymbol{v_m}\end{bmatrix} \quad \ldots(20)$$

Where $v$ is the new input thus far to be identified, note that formula (18) represents the plant and equation (20) represent the control input.

Substituting (20) into (18), The nonlinearity of the system is cancelled, resulting in a simple linear system as follow:

$$\begin{bmatrix}y_1^{r_1}\\ \vdots \\ y_m^{r_m}\end{bmatrix} = \begin{bmatrix}v_1\\ \vdots \\ v_m\end{bmatrix} \quad \ldots(21)$$

where $v_m$ is the linear controller output, which are the new control inputs for the linearized system.

## 5. Proposed Nonlinear Controller Design

To ensure an efficient tracking control for the terminal voltage and system speed, a non-linear FL could be utilized to uncouple the control of each output state. The resulting control of the whole system is presented in Figure 2

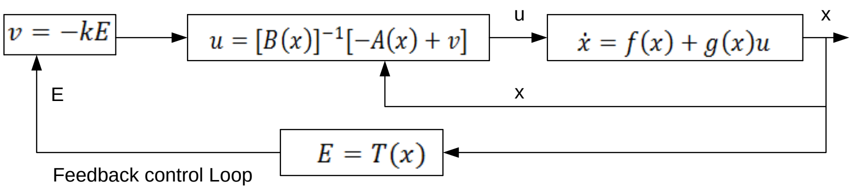


Figure 2. FL controller

The isolated motor generator set defined in equation (12) is in the same form as (14), so it is possible to express the variables in (14) and (15) as row vector transposers as following:

$$x = [x_1\, x_2 x_3 x_4 x_5]^T = \left[i_a\; i_d\; i_q\; i_F\; \omega_r\right]^T \quad \ldots(22)$$

$$g = \begin{bmatrix}0 & -a_4 & 0 & a_{11} & 0\\ \frac{1}{L_a} & 0 & 0 & 0 & 0\end{bmatrix}^T \quad \ldots(23)$$

$$u = [u_1 \quad u_2]^T = [v_a \quad v_F]^T \quad \ldots(24)$$

$$y = [\tilde{V}_s\,,\;\; \tilde{\omega}_r]^T \quad \ldots(25)$$

where $\tilde{V}_s$ and $\tilde{\omega}_r$ are defined as follow

$$\tilde{V}_s = \int\left(V_s - V_{ref}\right)dt \quad \ldots(26)$$

$$\tilde{\omega}_r = \int\left(\omega_r - \omega_{ref}\right)dt \quad \ldots(27)$$

The output variables $\tilde{V}_s$ and $\widetilde{\omega}$ characterize the errors integral between the factors $V_s$ and $\omega_r$ to be regulated and their reference $V_{ref}$ and $\omega_{ref}$. For ensuring zero steady-condition errors and increasing the controller's robustness if the system is subject to broad and rapid load variations, integral action is added to the control loop.

The new system is controlled now characterized by Eq.(22 )-(27) that is seven non-linear order model. To linearized and decoupled the state of this equation, the principle explained in section (3.4) is applied. Not all concept step are presented for the sake of simplicity, However by applying equations (17) we could get a new model described by equation (28) shown below, it could be noted that the input appeared in the first differentiation for $\tilde{V}$ while for $\tilde{\omega}_r$ the input appeared in the second differentiation.

$$\begin{bmatrix}\dot{\tilde{V}}\\ \ddot{\tilde{\omega}}_r\end{bmatrix} = \begin{bmatrix}A_1\\ A_2\end{bmatrix} + \begin{bmatrix}0 & -R_L a_4\\ \frac{k\,k_t}{L_a} & -k a_{12} a_{11} i_q\end{bmatrix}\begin{bmatrix}v_a\\ v_F\end{bmatrix} \quad \ldots(28)$$

Where:

$$A_1 = R_L\left(-(a_1 + a_5\omega_r)i_d + (a_2\omega_r - a_6)i_q + (a_3 - a_7\omega_r)i_F\right)$$

$$A_2 = -kk_t\left(\frac{R_L}{L_a}i_a + \frac{k_b}{L_a}\,\omega_r\right) - ka_{12}\left[a_8 i_q i_d - a_5\omega_r i_F i_d - a_9\omega_r {i_q}^2 - a_6 i_F i_q - a_{10} i_q i_F - a_7\omega_r {i_F}^2\right]$$

$$\boldsymbol{k} = \frac{\boldsymbol{p}}{(\boldsymbol{2j_2} + \boldsymbol{pj_1})}\,,\; a_{12} = \frac{3}{2}\frac{P}{2}L_m$$

As shown in Figure 2 above, to cancelled the nonlinearities in equation (28), the controlling input has the next procedure:

$\boldsymbol{u} = [\boldsymbol{B}(\boldsymbol{x})]^{-1}[-\boldsymbol{A}(\boldsymbol{x}) + \boldsymbol{v}]$ **…….(29)**

Where $v$ is the new vector of control inputs, and the next linear association is obtained between the new inputs,$v$ and output $y_d(x)$:

$y_d(x) = v$ ….(30)

Whereas $y_d(x) = \left[\dot{\tilde{V}},\ \ddot{\tilde{\omega}}_r\right]^T$

And $v = [v_1,\ v_2]$

Not that the total relative degree (r=2) of the system and the closed-loop system (Eqn (28)) consists of two decoupled linear subsystem. There is one first-order subsystem$\left(\dot{\tilde{V}}\right)$ and one second-order subsystem($\ddot{\tilde{\omega}}_r$).

A stabilizing controller for Eqn (25) is now easy to design. A state feedback controller is utilized. It has the equation as follows:

$v_p = -k_{pq}e_p$ ….(26)

Where $(k_{pq})$ is the matrix of feedback gain and $e_p$ represents the error between the output variables ($\tilde{V}_s$,$\tilde{\omega}_r$ ) and the reference signals. The following expression is therefore given to $v_p$:

$v_1 = -k_{11}\tilde{V}$ $\qquad v_2 = -k_{21}\tilde{\omega}_r - k_{22}\dot{\tilde{\omega}}_r$

The feedback gain matrix, $k_{ij}$ is selected such that the closed-loop system's value satisfies the conditions of Hurwitz's stability criterion. These are measured in just such a way that with a coefficient of damping 0.8, the slow mechanical speed dynamic stabilizes at 0.45 sec. The poles needed are identified correctly and are demonstrated in Table1. The closed-loop method is, therefore, asymptotically consistent, and the error between performance and comparison will correlate to zero.

Table 1. Closed-loop poles

| $\tilde{V}$ | $\tilde{\omega}$ |
|---|---|
| **-45** | **-11.2 ± 8.4i** |

## 3. Results

### 3.1. Simulation results

Simulations investigations were conducted in order to validate the state FL non-linear controller performance. The simulated synchronous generator is four poles. 2.5KW with the following parameters: $R_s$=3.1Ω, $L_s$=0.5H, $L_m$=0.32H, $R_F$=2.5Ω, $L_F$=0.25H, $\omega_m$=1500RPM and $V_{dc}$=35V. Initial conditions are $V_{ref}=200\sqrt{2}$ with a resistive load $R_L$=120Ω. The separately excited dc motor rated 5Hp, 250V, J=0.05Kgm$^2$. The test of simulation demonstrates the closed-loop system's response under a changeable load from $R_L$=60Ω to $R_L$=120Ω (this means the load decrease from full load to half) at t=1sec. Figure 3 illustrate the reaction of the motor-generator set speed; the figure shows the good performance of the controller for tracking reference speed. Figure 4 shows the stator voltage dip the controller shows good voltage recovery to reference terminal voltage. The system input represents two voltage, motor armature voltage Va and fields excitation voltage Vf. Figure 5 shows armature voltage variation $V_a$ which fed the motor through back chopper we noted the increased chopping frequency at time t= 1sec to decrease the average dc motor voltage, and Figure 6 also shows field voltage response to load variation. The feedback obtains $k_{pq}$ of the non-linear controller, specified in Table 2.

Table 2. Controller gain

| Controller Gains Description | value |
|---|---|
| $\tilde{V}$ gain | $K_{11}$=300 |
| **$\tilde{\omega}$ gain** | [$K_{21}$, $K_{22}$]=[41, 2].10$^3$ |

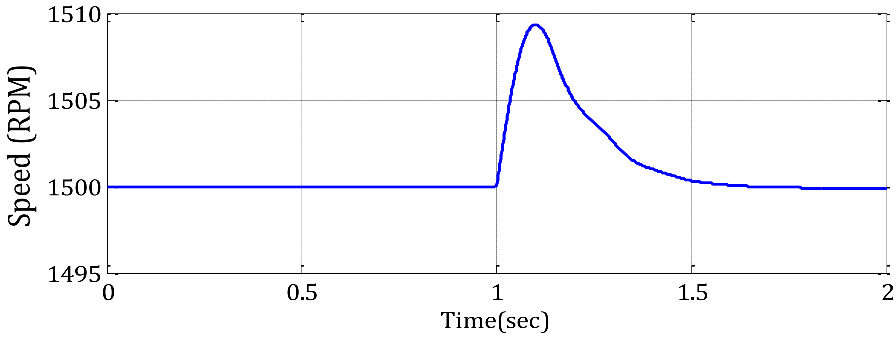


Figure 3. Speed response of the system.

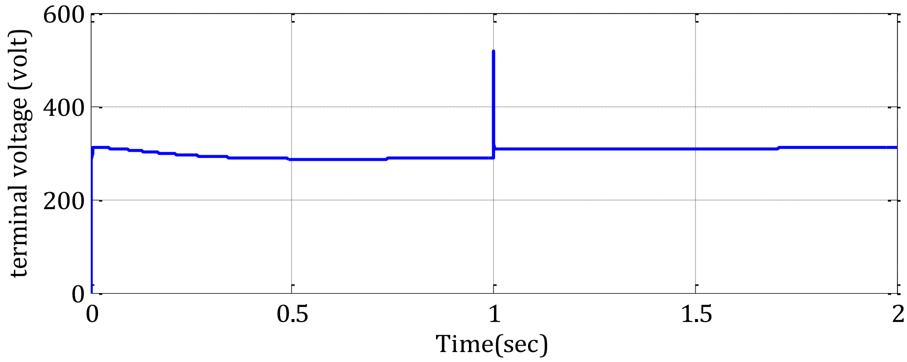


Figure 4. Stator terminal voltage dip during load change

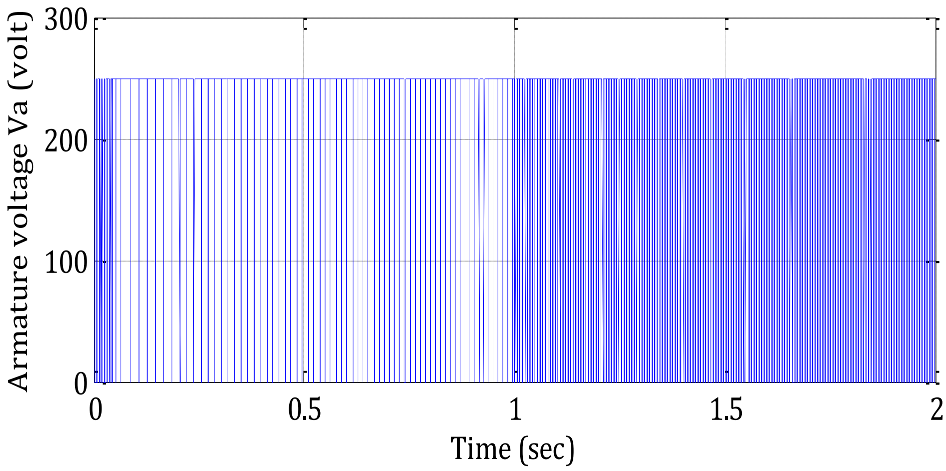


Figure 5. DC motor armature voltage

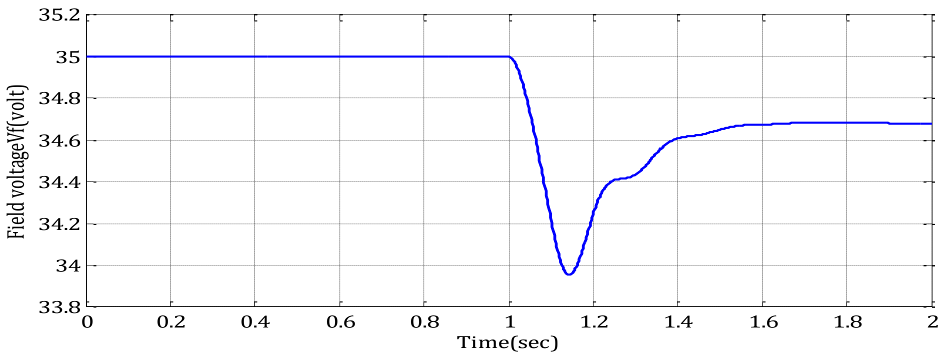


Figure 6. Field voltage response

## 4. Experimental results

The controller has been tested in a prototype machine. The synchronous generators rated 4.5 KVA, 4poles 3 phase machines. The separately excited dc motor rated 280 V, 1500 rpm is utilized as a prime mover. A full-bridge DC/DC power converter connected to the field circuit which could provide ±100V DC. The resistive load is collected of 2 banks with a full or half load magnitude ($R_L$ =128Ω & $R_L$=64Ω).
The control algorithm is designed using a Texas floating-point 150MHZ (DSP TMS320F28335) device. For the calculation of rotor location and dq current, a two-differential sensor is used. DSP from a personal computing device that is programmed. For simplifying the code execution of the DSP without utilizing the C code, Matlab/Simulink Real-Time Workshop C code development is used.
As an editor, the Simulink environment is used to code optimization techniques utilizing the particular blocks established for the TMS-F2800 DSP cards group.
Depending on the DC/DC power conversion functionality, the sample period is set at 10-4sec, which correlates to 10KHz as the highest frequency. The experiment test relies on the configuration of the regulator in section 5—the first validating test, under a load adjustment, the device reaction. The reference line power is calculated to 380 Vrms (Vref = 220 √2), and unexpectedly, at 0.1 sec, the load is adjusted from half to maximum. Figures 7-9 shows a three-phase stator voltage. As expected, the controller success to fast regulates the stator voltage amplitude.

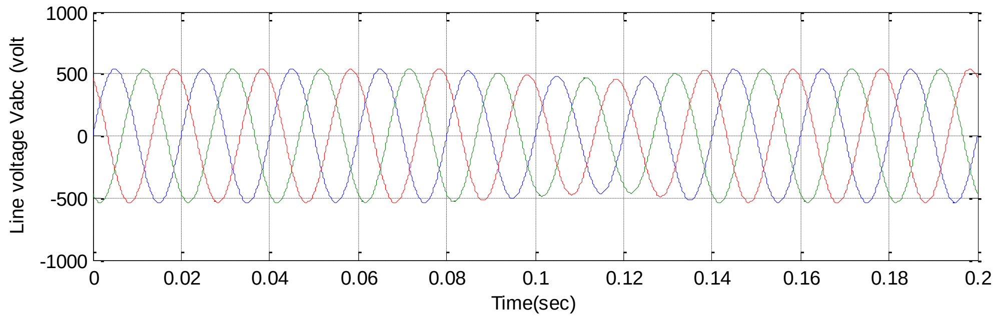


Figure 7. Three-phase stator voltage

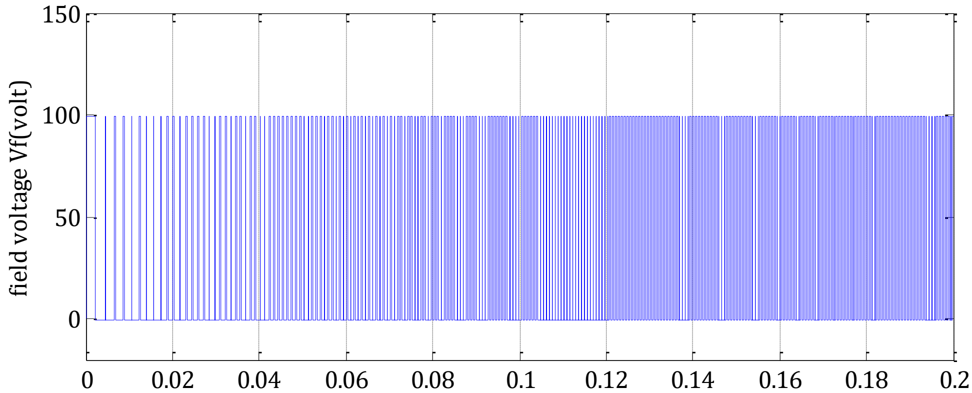


Figure 8. Field voltage

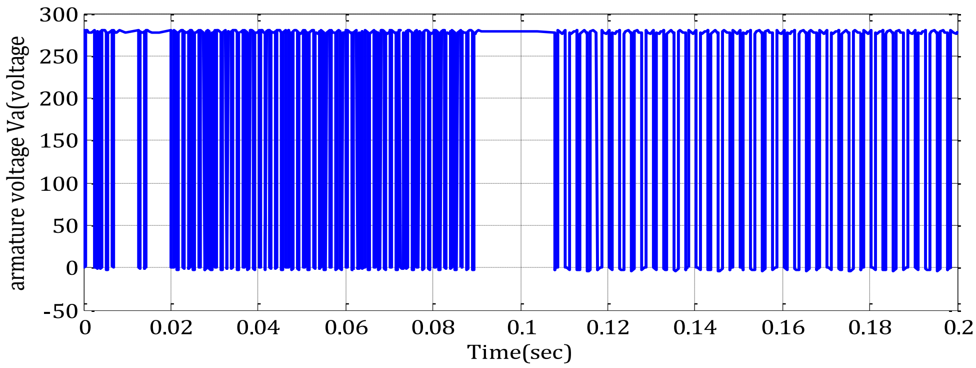


Figure 9. Armature voltage

## 5. Conclusion

In this paper, the linearization of output-input state feedback considered by a non-linear controller is designed to regulate the speed and isolated voltage stator amplitude of motor-generator set that feeds an isolated resistive load. A motor-generator set has been modelled as a MIMO non-linear system with speed and stator terminal voltage is utilized as the system output states, while motor armature voltage and field voltage are the system input. For ensuring zero steady-condition error if the points shift operating, the integrator is inserted into the control loop. A speed tracking controller and field voltage controller are designed depending on the functional transfer of the transformed linear system using pole placement design method. The results of experimental and simulation clearly show that the system has a good recovering ability to the initial state when the system subject to high load variation. Future work would deal with the extension of proposed mythology by including the chopper feeding armature voltage and field voltage as well as uncertainties within the overall system.

Appendix A:

$$a_1 = \frac{R}{L_{eq}}, a_2 = \frac{L_s}{L_{eq}}, a_3 = \frac{L_m R_F}{L_{eq}\ L_F}, a_4 = \frac{L_m}{L_{eq}\ L_F}, a_5 = 1, a_6 = \frac{R}{L_s}, a_7 = \frac{L_m}{L_s}, a_8 = \frac{L_m R}{L_F L_{eq}}, a_9 = \frac{L_m L_s}{L_{eq} L_F}$$

$$a_{10} = \left(\frac{R_F}{L_F} + \frac{{L_m}^2 R_F}{{L_F}^2 L_{eq}}\right), a_{11} = \left(\frac{1}{L_F} + \frac{{L_m}^2}{{L_F}^2 L_{eq}}\right), L_{eq} = \left(L_s - \frac{{L_m}^2}{L_F}\right)$$

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