DQ model of PMSG with the most proficient dynamic analysis in standalone grid

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Abstract

The pico grid implements an essential solution to provide electrical power for isolated areas like villages and remote regions. Wind, tidal or hydropower, etc., may be the energy source for these grids. This application can be effectively served by a permanent magnet synchronous generator (PMSG), which is a very convenient option. In this work, the generator's prime mover is a regular speed source that mimics a pico-hydro turbine. Using park transformation, the dynamic model was built and employed in Matlab/Simulink to study the system's response with different perturbations for operation at constant and variable of load, rotor speed, and flux. The results of the proposed system model show a smooth voltage and current output.

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1. Introduction

Renewable energy sources (RES) consider a solution in terms of providing electricity for isolate societies which located remotely from the national grid (NG)(F. AL Kababjie & H. Hamdon, 2013); also, the case of providing power is a more economical solution than depending on NG(Williamson et al., 2017). another reason for the developed interest in the RES is to preserve the environment from gaseous emissions resulting from dependence on traditional energy sources such as coal and other fossil fuel sources(Ghanim & Alsammak, 2020); also, there are some countries face difficulty to provide fossil fuels, either due to economic difficulties, or because they are not naturally available to them, or due to geopolitical complication, like what happened in the recent crisis between Russia and Ukraine.

Based on what was mentioned above, it is clear that the dependence on the RES maybe not be a choice but a fact, and from that point, the study of that energy source in terms of being more familiar with its weak points to overcome it, or to increase the efficiency of its generation components is a significant concern.

Pico hydro turbine considers a friendly environment source of energy that depends on the flowing of water to produce electricity(Praptodiyono et al., 2021). In this paper, the hydro turbine is assumed to be a pico one in which it produces lower than 5kw(Zainuddin et al., 2009). the main difference between hydro and other RES like tidal or wind, that it is approximately has a constant speed, where the speed of water flow changes seasonally, not like wind turbines where the speed varies in less than a minute, so in this paper, a constant speed source will be assumed as a simulation to the pico hydro turbine.

Various types of generators are used with the hydro turbine, but the most typically used with pico grids is the PMSG generator(Murali Krishna et al., 2022) because it has a permanent excitation, not like a winding rotor, so it needing for maintenance is limited due to the absence of rings and brooms(Fateh et al., 2016); also the development in material science regarded to hard magnetic materials, make the characteristics of PMSG became more efficient and compact(Quintal-Palomo et al., 2021). Another advantage of using PMSG is that the slow rotor speed does not need the gearbox in direct drive machines (Wang et al., 2014).

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The representation with DQ model has excellent importance like the easiness of depending on the constant variable with time(Rotor reference frame), compared with the variable in the ABC stationary frame, which varies instantaneously with time. Hence, designing the control circuit is much easier with this model(Ghanim et al., 2022), also the use of models in the study of PMSG production provides insight into many abnormal situations, such as what happens to the magnet in terms of demagnetizing impact owing to increased temperature or some sorts of defects in general(Uršič & Nemec, 2019).

Many authors dealt with the analysis of PMSG in the previous works of literature; (Mohan & Vittal, 2018), (Hossain et al., 2017), (Bisoyi, 2013)& (Anbarasan et al., 2021); all of them studied the modelling and simulation of standalone PMSG-based wind energy conversion system. The co-simulation approach in dealing with the modelling of PMSG was presented by (Quintal-Palomo et al., 2019) paper. (Chandran et al., 2018) Discussed the existence of PMSG in the small hydro system with a vision to improve the generated voltage. (Fukami et al., 2010) Analysed the behavior of salient pole PMSG in a model derived from the dynamic model. (Williamson et al., 2017) mentioned how to model and simulate the pico-hydro power in an isolated grid. (Zainuddin et al., 2009) Studied the design of a pico hydro generation system using the consuming water distributed to houses. The machine rating used in the paper was taken from (Eduardo & Palomo, 2019), where R_s=5.56Ω, L_d=L_q=11.3e-3 H, Npp=2, λr=0.8 wb, 1500rpm.

In this work, Matlab-Simulink will be used to create a DQ model. Then Different simulations will be done under multiple input/output perturbations to provide knowledge about the machine behavior under these perturbations, which can be used later to propose an efficient control algorithm to set the generated voltage at permissible limits.

2. System design:

2.1 Pico hydro turbine:

The hydrolic power available from hydro turbine type undershoot waterwheel is given in Eq (1) :

$$P_{hyd} = 0.5\rho A v^3 \tag{1}$$

So the mechanical power transferred depends on the efficiency of the turbine according to

$$P_m = \eta_{hyd} P_{hyd} \tag{2}$$

In which the turbine efficiency is a function of a constant of the turbine named C given in:

$$\eta_{hyd} = 2C\left(1 - C^2\right) \tag{3}$$

In this context, 'p_{hyd}' represents hydraulic power, 'p_m' denotes mechanical power, 'ρ' signifies water density, 'v' indicates water speed, 'A' represents the swept area by the water wheel, and 'C' is a constant with an approximate value of 1/3 for this particular type of hydro turbine.(Denny, 2004)

2.2 Permanent magnet synchronous generator (PMSG):(Kamruzzaman Khan Prince et al., 2021)

The dynamic model of the PMSG is derived by applying Kirchhoff's voltage law on the circuit of Fig.(1), then the stator DQ voltages are given by Eq. (4) & (5):

$$v_{ds} = -R_s i_{ds} + \omega_r L_q i_{qs} - L_d \rho i_{ds} \tag{4}$$

$$v_{qs} = -R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r - L_q \rho i_{qs} \tag{5}$$

Where v_{ds}, v_{qs}, i_{ds} & i_{qs} are stator DQ axis voltages and current, while R_s, L_d & L_q are the stator winding resistance and inductance for direct and quadrature axis, finally λ_r, ω_r are the rotor flux and mechanical rotational speed.

With some mathematical manipulation, the stator current equations can be written as shown in eq. (6) & (7):

$$i_{ds} = \frac{1}{SL_d}\left(-v_{ds} - R_s i_{ds} + \omega_r L_q i_{qs}\right) \tag{6}$$

$$i_{qs} = \frac{1}{SL_q}\left(-v_{qs} - R_s i_{qs} - \omega_r L_d i_{ds} + \omega_r \lambda_r\right) \tag{7}$$

The electromechanical torque induced in the stator due to the reaction between rotor and stator fluxes is given in Eq(8):

$$Te = \frac{3P}{2}\left(\lambda_r i_{qs} - \left(L_d - L_q\right) i_{ds} i_{qs}\right) \tag{8}$$

for non salient pole machine $L_d=L_q$, so eq.(8) becomes:

$$Te = \frac{3P}{2}\left(\lambda_r i_{qs}\right) \tag{9}$$

The active power in the DQ frame can be calculated from eq.(10):

$$P = \frac{3}{2}(v_{ds}\,\mathrm{i}_{ds} + \mathrm{v}_{qs}\mathrm{i}_{qs}) \tag{10}$$

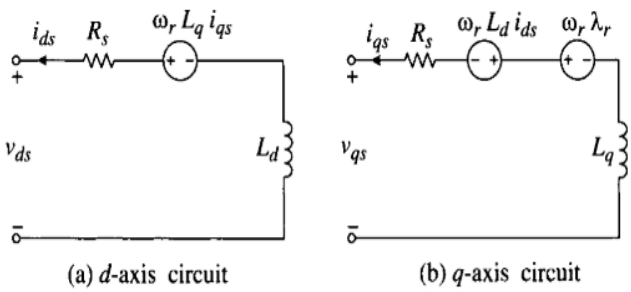


Figure 1. PMSG's dynamic equivalent circuit in the quadrature axis

The Matlab Simulink software was utilized to create Fig. (2) by employing the Simulink Library, incorporating equations (1) to (10) into the simulation.

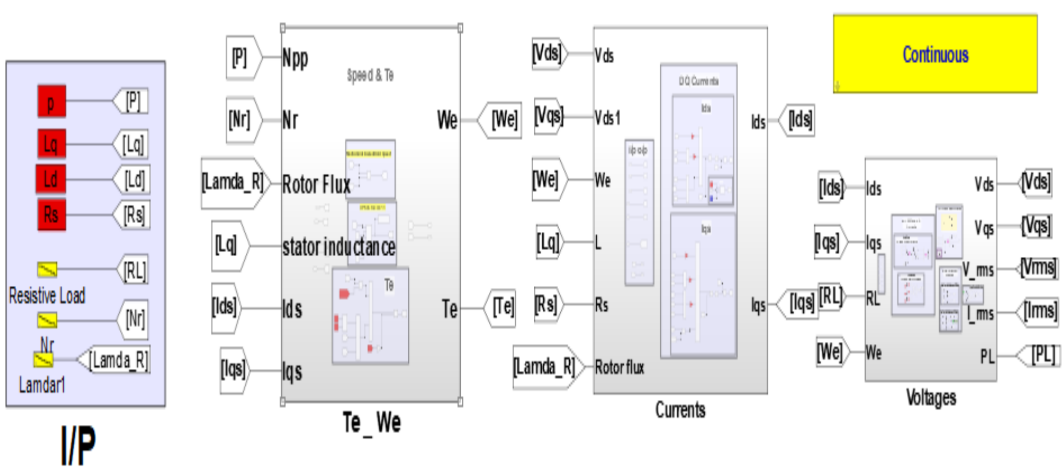
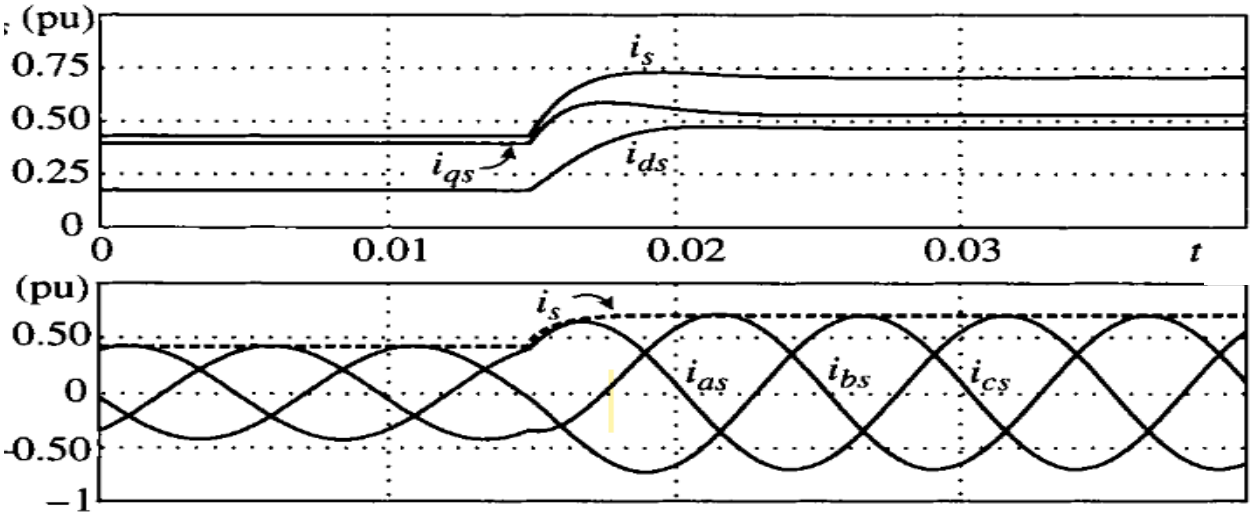


Figure 2. PMSG's dynamic model in Matlab/Simulimk

3. Results and discussion:

3.1 Model validation

The model was validated by comparing the results of (BinWu & Kouro, 2011) model, which is shown in Fig.(3), and the results of the created model, which is shown in Fig(4), for the same rating and operation conditions; the comparison showed that all results were identical.



Time(sec)

Figure 3. Bin wu's two & three phase instantaneous & rms currents

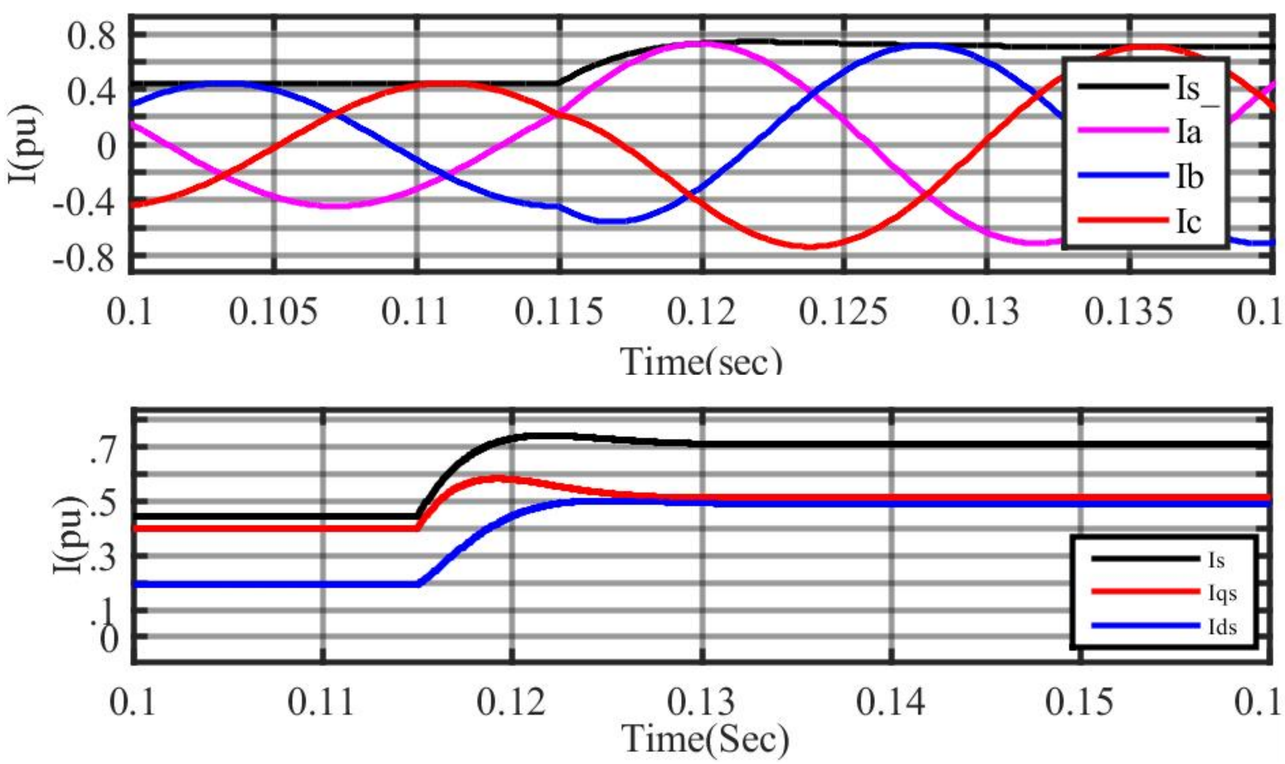


Figure 4. Proposed model's two & three phase instantaneous & rms currents

3.2 Operation at resistive load

3.2.1 Constant load, rotor speed, and flux

After the successful loading of the model with the aforementioned specifications as outlined in the introduction, it was operated with a rotor speed of 1500 rpm, a load resistance of 56 ohms, and a rated rotor flux. The results shown in Fig. (5) & Fig. (6) explain the instantaneous three-phase voltages and currents, which, in turn, have been obtained by using park transformation as a part of the proposed model. In contrast, the results in Fig. (7) were obtained from measurement models built depending on the basic law of power and torque. In Fig. (8), the sum of copper losses power and electromagnetic power equals the input mechanical power.

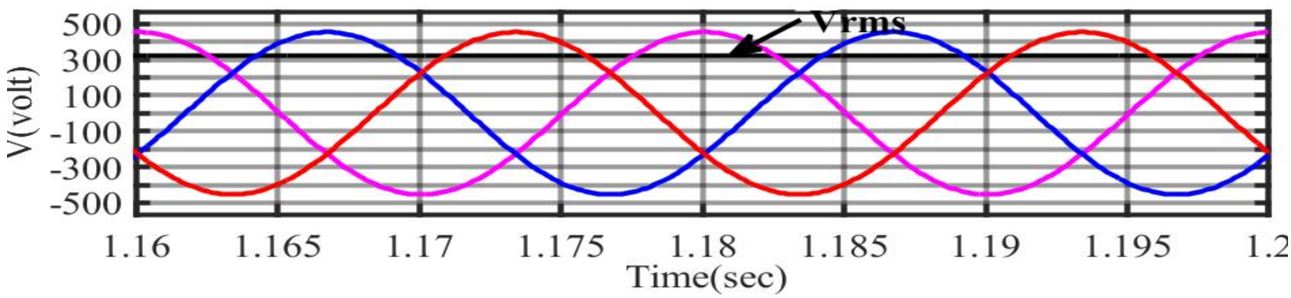


Figure 5. Three phase instantaneous & rms voltages

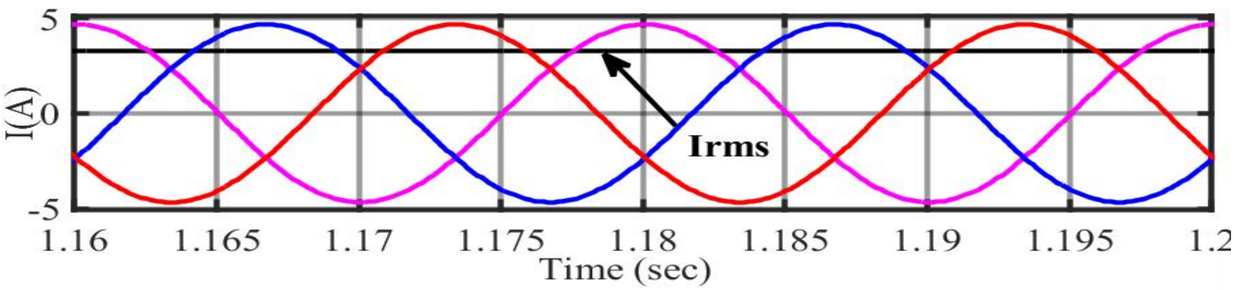


Figure 6. Three phase instantaneous & rms currents

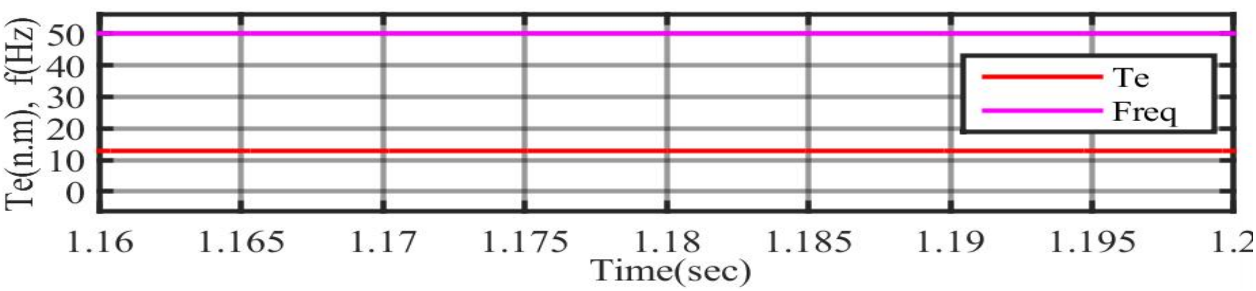


Figure 7. Measured electromagnetic torque and frequency

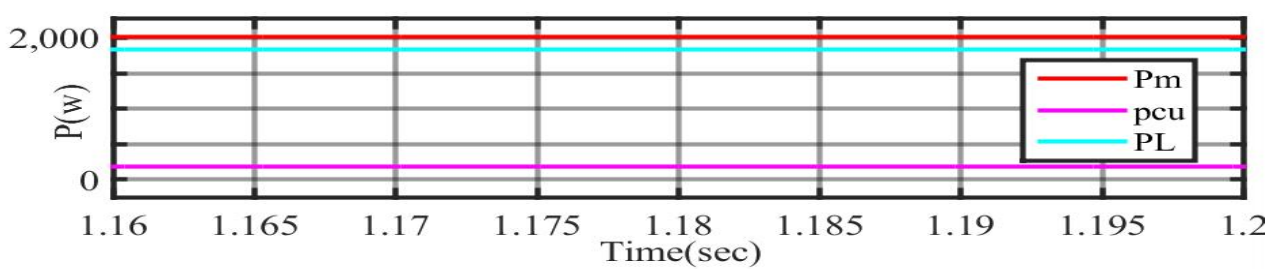


Figure 8. The power for the mechanical (Pm), copper loss (Pcu) & load power (PL)

3.2.2 Constant, speed, variable load & rotor flux

In this operation case, the speed was kept constant at 1500 rpm while both load and rotor flux was changed; Fig. (9) shows the effect of changing the last mentioned quantities on the power vs terminal voltage relation for different values of rotor flux. As a result of the demagnetizing impact caused by an excessive increase in rotor temperature or corrosion, the rotor flux may decrease, while the overrated case also falls under this study, where permanent magnets may be redesigned to greater values to overcome voltage drops due to armature resistance with increased load currents.

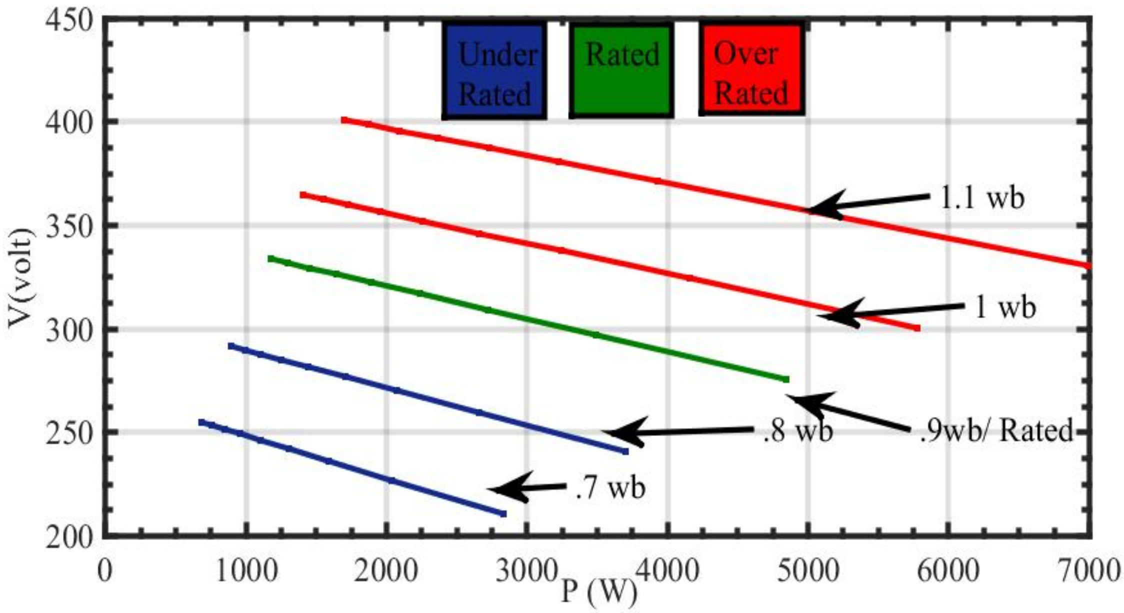


Figure 9. Terminal voltage vs generated power for multiple values of rotor flux

3.2.3 Constant load, variable speed & constant rotor flux

Here, the only variation is due to rotor speed, Fig. (10) shows how the voltage and output power behave with the changing in the mechanical input rotation.

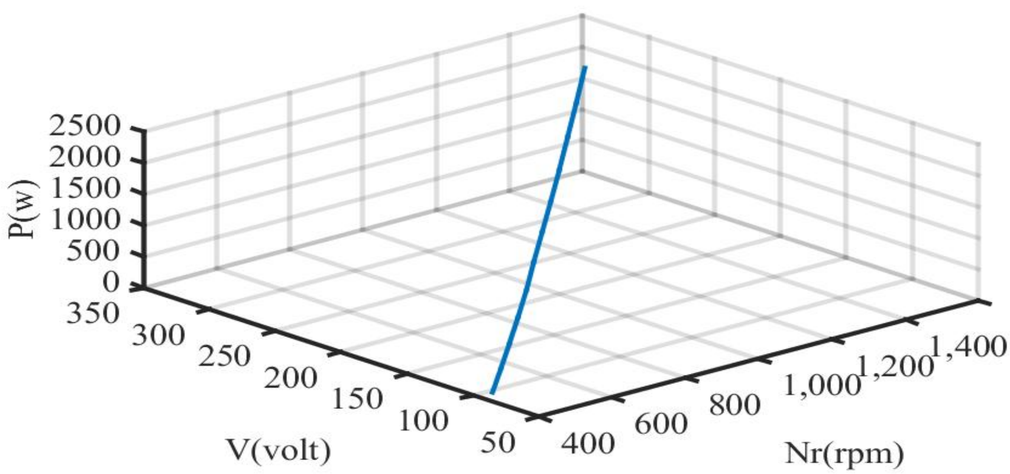


Figure 10. Terminal voltage, generated power vs Rotor speed

3.2.4 Variable load constant speed & rotor flux:

Fig(11) shows the relation between terminal voltage and output power for various load values at constant rotor speed and flux.

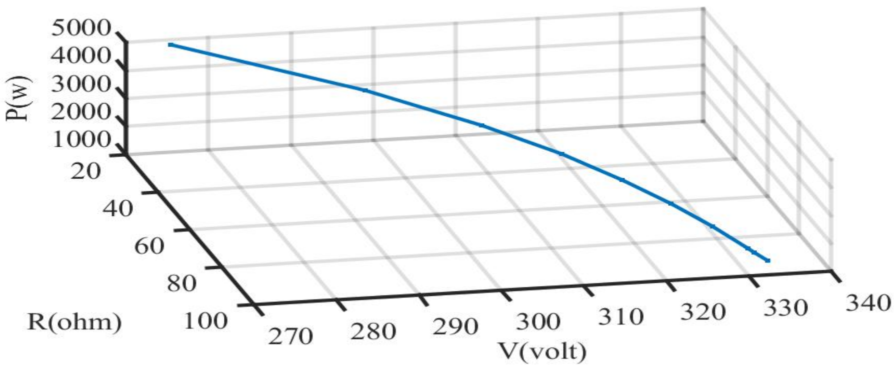


Figure 11. Terminal voltage, generated power vs variable load

4. Conclusions:

Different simulations cases performed with the proposed model show that the disturbances in performance are either constrained externally by changes in mechanical input/ output or internally by changes in rotor flux caused by demagnetizing effects, which results in a factor of time, high temperatures at faults or corrosion effects. These results have indicated the importance of exciting control systems to set the magnitude and frequency of the generated voltage at the rated limits to meet the consumer's needs. The proposed model provides a successful environment to predict the machine's behavior to develop these control algorithms or to modify the machine design, all of that were done by a simple, robust, and understandable model.

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Conflict of Interest

Authors declare that there is no conflict of interest.

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