Implementation and Performance Analysis of a Switched Reluctance Motor Fed from Non-Energy Stored PV System

S. B. Efe, B. Kocaman and D. D. Aktaş

Abstract— **In this paper, an actual system that consist of a switched reluctance motor (SRM) and photovoltaic (PV) generation was analyzed to determine operational behaviors in terms of both generating and motor units. System was designed without an energy storage unit. This type of design allows obtaining more convergence and actual results during operation in different conditions. According to this aim, a system that includes such structures was constructed physically. System was operated and observed for different weather and loading conditions. As the proposed system was aimed to use for agricultural electrical vehicle applications, results were discussed by using graphs that obtained from various points, especially in terms of these approaches.**

Index Terms— **Photovoltaic system, power system analysis, renewable energy sources, switched reluctance motor.**

I. INTRODUCTION

TECHNOLOGICAL DEVELOPMENTS increases the energy use in acceleration and the conventional energy sources cannot meet this demand. It became vital to integrate renewable energy sources to main grid for supplying quality and continuous energy to customers. One of the major loads in power systems are motor loads. As it is known that motor parameters are directly affect from supply parameters like voltage and current, in this study, a switched reluctance motor (SRM) that supplied by a photovoltaic (PV) system is analyzed during various operating conditions. It is aimed to obtain operational data to determine the motor efficiency while supplied by a renewable energy source. System was designed as not to include any storage unit like battery. This allows researchers to test the motor in limited supply capacity conditions and obtain more actual results. According to this aim, literature was reviewed for PV systems and motor applications. Studies on PV applications, which include design [1-3] and analysis [4-6] of such systems, can be observed widely in literature. It is necessary to analyze the PV modules for energy output characteristics because of the mismatch losses and shading losses of such structures. PV system studies are divided into two in general as grid connected [7-8] and islanded or standalone [9-10] modes of operation. In addition, researchers are focused on the various types of motors as loads for PV systems. These papers are classified as induction motor [11-12] and DC motor [13-14] supplement. Besides the classical electric motors, in this research, SRM is chosen to use its advantages as given in following sections. The paper was designed as following; in section II mathematical models of system components, which are PV system and SRM, were given. Performance analysis was performed in section III and results were discussed in section IV.

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II. MATHEMATICAL BACKGROUND

Mathematical representation of the system elements have to be given for a better understanding of performance analysis results besides physical structures. Therefore, mathematical models and actual system components of PV system and SRM are given in subsections A and B respectively.

A. *Photovoltaic System*

The PV effect is the creation of voltage or electric current in a material upon exposure to light. PV system works on the principle of photovoltaic effect, direct conversion of photonic energy to electrical energy using PV cells. The power generated from these PV cells depends directly on the level of solar irradiation [15].

Detailed analysis and study is necessary for an appropriate design of PV systems. Therefore, it should be started from cell level for better understanding. PV panels are formed by connecting photovoltaic cells series and parallel, which are created by semiconductor materials. General structure of a PV cell is given in Fig. 1. [16-18].

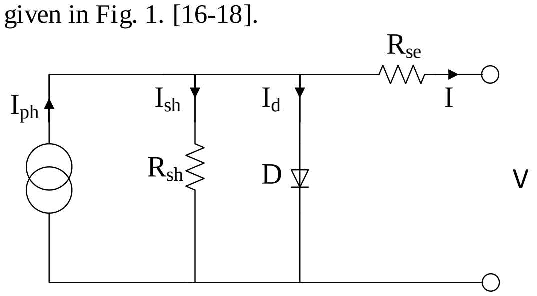

Fig. 1. PV cell circuit

According to the given equivalent circuit, mathematical model of a PV cell can be described as:

$$I = I_{ph} - I_d - I_{sh} \tag{1}$$

$$I = I_{ph} - I\left[e^{q(V+IR_{se})/kT} - 1\right] - \frac{V + IR_{se}}{R_{sh}} \tag{2}$$

In Equation (2), I shows the current, V represents the terminal voltage, q shows electron charge, k is the Boltzmann constant and T is the ambient temperature in terms of Kelvin. According to the design, Equation (2) can also be rewritten to obtain output voltage.

In this study, a PV system that is physically installed at Bitlis Eren University Rahva Campus is used as energy source for SRM. This structure is given in Fig. 2.

Fig. 2. PV panel and inverter

There were six PV panels, each has a power of 150 W, and a 24/220 V full sine inverter with a power of 3000 VA used for PV system.

B. *Switched Reluctance Motor*

SRM can be considered as an alternative to conventional electric machines. It is cheaper and simpler than the same powerful conventional machines because of the improvements in motor drive technology [19-20].

The equivalent circuit of SRM is shown in Fig.3. In this circuit, output emf can be modeled as a current controlled voltage source. Due to the saliency on rotor and stator side, SRM has non-sinusoidal current and flux across all windings.

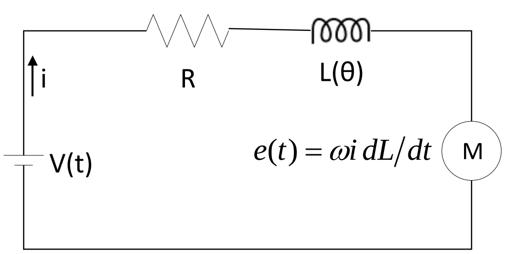

Fig. 3. SRM equivalent circuit

According to the Fig. 3, voltage equation for one phase can be given as,

$$v = Ri + \frac{d\psi}{dt} = Ri + \frac{d(Li)}{dt} = Ri + L\frac{di}{dt} + i\frac{dL}{dt} \tag{3}$$

$$= Ri + L\frac{di}{dt} + i\frac{dL}{d\theta}\frac{d\theta}{dt} \tag{4}$$

And finally

$$v = Ri + L\frac{di}{dt} + \omega_m i\frac{dL}{d\theta} \tag{5}$$

where v is terminal voltage, R is phase resistance, i is current, ψ is flux, L is phase inductance, θ is rotor position and ω_m is angular speed in rad/s.

Power value can be obtained as

$$P = Vi = Ri^2 + L_i\frac{di}{dt} + \omega i^2\frac{dL}{d\theta} \tag{6}$$

As the torque equation is

$$T = \frac{P}{\omega_e} \tag{7}$$

Then the torque Te that can obtained from the motor

$$T_e = \frac{1}{2}i^2\frac{dL(i,\theta)}{d\theta} \tag{8}$$

Similar as other motors, for SRM, torque is limited by maximum allowed current, and speed by the available terminal voltage, which is illustrated in Fig. 4.

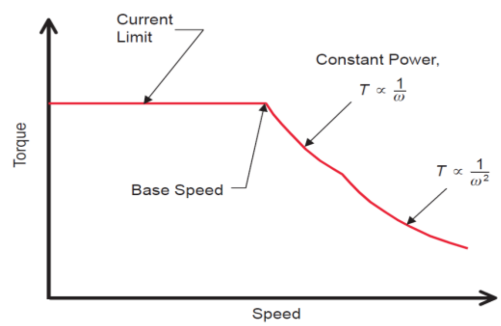

Fig. 4. SRM Torque – Speed Characteristics

Switched reluctance motor (SRM) has the advanced capability as it is the most suitable motor for variable speed applications like solar photovoltaic (SPV) array fed water pumping system. A PV pumping system using SRM is analyzed in [21-22] but it has some drawbacks due to use of battery [23]. The torque-speed operating point of an SRM is essentially programmable and determined almost entirely by the control. This is one of the features that makes the SRM an attractive solution for various applications [24].

An 8/6 SRM with an intelligent control unit was used in this study. SRM with intelligent control unit is shown in Fig. 5, where properties of the SRM that was used in system are summarized in Table 1.

Fig. 5. SRM and controller unit

TABLE I
SRM PROPERTIES

Parameter	***Value***
Phase	1 ϕ
Nominal Voltage	220 V
Max. Power at Nom. Voltage	1400 W
Rotor Speed	50 to 5000 rpm

III. EXPERIMENTAL PERFORMANCE ANALYSIS

Proposed system was tested for different operating conditions to obtain performance data. Fluke 435 power and energy analyzer was used for measurement. As the system has no storage unit, PV generation directly affect the SRM. Therefore, system was observed in two cases, first was for different loading conditions in case of full irradiance and second in case of partial shading. A powder-brake unit with torque controller, which is shown in Fig. 6, was used to adjust loading values.

Fig. 6. Load unit

A. *Case 1- Nominal irradiance conditions*

In this case, system was tested when the PV had nominal irradiance. SRM was adjusted to operate at 1000-rpm rotor speed, loaded with 15%, 30%, 45% and 60% respectively in such condition and results were summarized in Fig. 7.

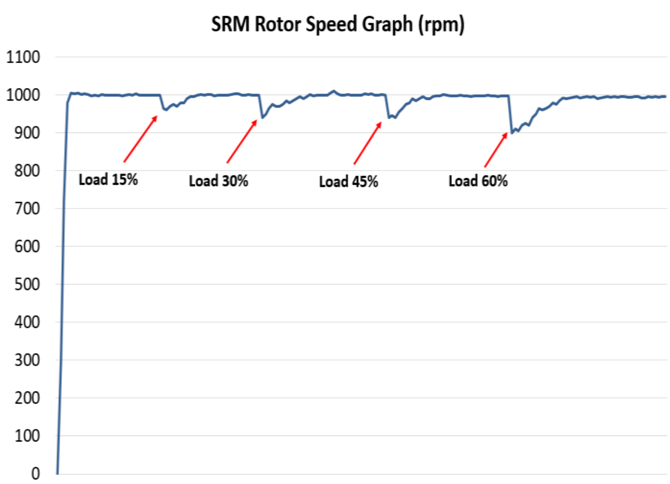

Fig. 7. Rotor speed during nominal irradiance

It is clear from Fig.7 that SRM could regulate the speed via intelligent control unit in nominal irradiance conditions. As there was a decrement in rotor speed, it was in tolerance limits that can be ignored. Therefore, it can be assumed that motor works efficiently under proposed conditions.

B. *Case 2- Partial shading conditions*

As it is common to occur irradiance decrement in case of possible shading at PV panels because of meteorological effects and dust, system was analyzed to obtain operational data for such conditions. In this case, irradiance was decreased 20% and 40% manually. Motor was loaded 15%, 30%, 45% and 60% for each level and results of 20% and 40% irradiance decrement were given in Fig. 8 and Fig. 9 respectively.

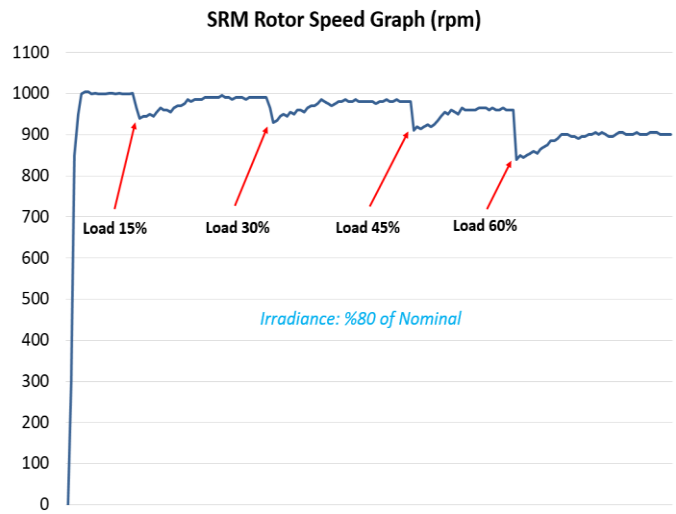

Fig. 8. Rotor speed during 80% of nominal irradiance

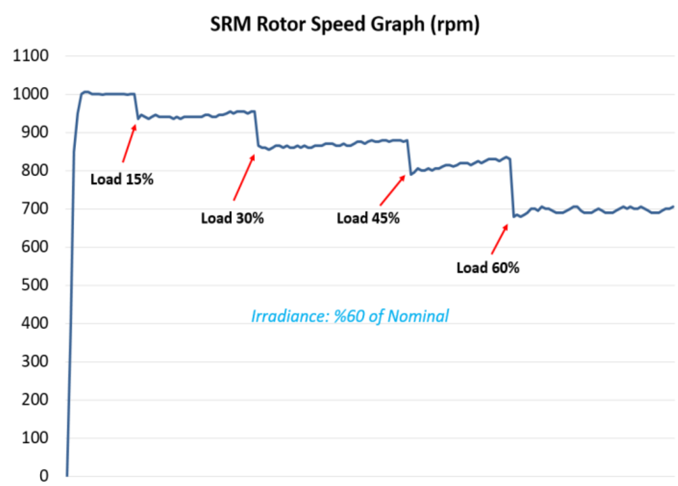

Fig. 9. Rotor speed during 60% of nominal irradiance

As irradiance is the major parameter of PV generation, it is clear from Fig. 8 and Fig. 9 that decrement in such parameter affect motor speed especially when loading value increased. Unlike the *Case 1* results, as expected, motor speed cannot be recovered to nominal speed. However, it still continues to operate and shows stability in speed characteristic. Speed can be regulated by controlled load-shedding in case of generation level decrement by a closed loop algorithm.

IV. CONCLUSION

In this study, a SRM is analyzed under different operating conditions to obtain the behaviors in case of renewable energy source based supplement. These behaviors are vital for agricultural applications and especially to use SRM in PV supplied electric cars. For such aim, system is analyzed for direct PV-fed mode of operation. Various loading and irradiance conditions are tested and results are discussed by using system graphs. It is clear that SRM is appropriate in using non-storage unit systems that have limited capacity of energy with an appropriate controlling unit. In case of decrement in generation values, motor speed can also be regulated by controlling loads. It should be noted that all meteorological effects are applied to experimental system and these affect results directly. Authors are in process of determine data for various conditions and applications.

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