

# SENSORLESS OPERATION OF 8/6 SR MACHINE WITH THE SELECTION OF OPTIMUM CONDUCTION ANGLE BASED ON MULTI OBJECTIVE PARTICLE SWARM OPTIMIZATION

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**Abstract:** This paper presents a sensor less scheme to obtain an optimum operating period for each load variation in the 8/6 switched reluctance motor. The drawbacks of using a position sensor in dusty environment are eliminated in this approach. Here, the operating parameters are fed back to the Adaptive Neural Network (ANN) controller. This model is developed efficiently and trained under supervised learning method in which flux-linkage and phase-current are fed as input and rotor position is estimated as output. Multi objective particle swarm optimization (MOPSO) based optimization technique is used in determining the optimum operating angle for the SR machine. The finalized model consist of ANN based position prediction loop, MOPSO based optimum angle selection loop with rigid current controller. The main objective of the model concentrates on maximizing the average torque with minimum torque ripple in the optimized operating region under various loading conditions with removal of position sensor. This system has the advantages of robustness, simple construction, reduced manufacturing cost with the absence of position sensor etc. The simulation is carried out in MATLAB/SIMULINK and Hardware is implemented using dsPIC.

**Key words:** Artificial Neural Networks (ANN), Switched Reluctance Motor (SRM), MOPSO, simulation, MATLAB, optimum angle, sensorless, position sensor, dsPIC ,

## 1. Introduction

Switched Reluctance Machine (SRM) were first developed in the early 1920's [2]. But the losses faced in electromechanical energy conversion are power electronic switches sets a major drawback in further advancements. After the improvements in the field of power electronics, the SRM machines were reintroduced since 1960s. It has been used in many commercially adjustable speed applications due to its unique mechanical structure and simple power electronic drive requirements. The intrinsic simplicity and

ruggedness made it superior to other electric machines [3]. Although numerous benefits offered by SRM such as performance, low cost, high speed and acceleration capability, it has disadvantages cause by non-linear characteristics of SRM such as torque ripple, acoustic noise and position sensor. It can be run only when the motor is integrated with power converter, controller and rotor position sensor. Many papers have been reported on the performance simulation of SRM with experimental validation for different control strategies. SRM need to detect the rotor position with a position sensor attached to the motor shaft. A position sensor, an encoder, a resolver, or a Hall sensor is normally used. The uses of these sensors cause increased cost and machine size, and reduced reliability. Therefore, several sensors-less drive techniques have been reported. The SRM machines are ordinary looking, easy to manufacture and of low cost [4]. The key factor for this is attributed to the power electronics. The uniqueness of the machine lies in the fact that it is combined with the power electronic switches [5]. The modelling of 8/6 pole SRM machine here is done with electromagnetic and electro- mechanical equations [6]. The sensor less operation of the aforementioned SRM is done with the ANN controller. The work is simulated using MATLAB/SIMULINK and results are obtained [7]. Many methods have been devised to minimize the torque ripple, complexity in control, non-linearity [8]. But, the increasing trend in this torque ripple minimization is the implementation of controllers for determining the optimum turn on angle and turn off angle and other parameters like reference current and size of hysteresis band [9]. This optimization of turn on and turn off angle reduces torque ripples and increases average torque [10]. Though turn on and turn off are each done by separate controllers, more importance is given to turn on control for minimizing torque ripple [11] and increasing the torque value is done by turn off angle control. MOPSO algorithm is used for deriving the optimum turn on and turn off angles and it is compared with PSO results. Sliding mode controller is used for speed control. It eliminates the drive nonlinearity and sets up a state space [12].

Since the torque generation in SRM is subject to rotor position, position sensing is mandatory [13]. However, using external sensors like resolvers and optical sensors have their own drawbacks. High cost, losses due to noise and problems with mechanical mounting usually drowns their importance with accuracy and efficiency [14]. Using sensor less control with optimized operating angle eliminates this demerits and increases the flexibility of SRM. Further dual mode operation of this SRM eliminates the battery storage problem and increases the efficiency of the whole system with regenerative power.

## 2. Modelling of SRM for dual mode operation

The SRM has to be modelled to avoid discrepancies caused by non-linearity due to double saliency of the machine, leading to non-linear torque and current. Therefore, mathematical modelling is done relieving from the tedious reference frame theory. To simplify it even more, leakage flux, magnetic saturation characteristics are neglected. The Figure 1 below shows the rotation of rotor with respect to stator for an angle of 15 degrees.

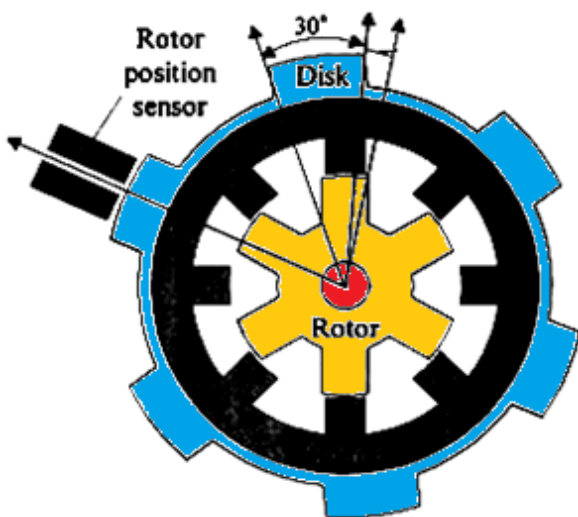


Figure 1 8/6 Switched Reluctance Motor

The voltage equation for motoring mode of SRM is given by

$$V = I_a R_a + e + L \frac{di}{dt} \text{ ----- (1)}$$

Equating  $e$  to a function of inductance,

$$e = \omega_m \cdot i \frac{dL}{d\theta} \text{ ----- (2)}$$

$$V = i_a R_a + \omega_m i \frac{dL}{d\theta} + L \frac{di}{dt} \text{ ----- (3)}$$

The power absorbed by the SRM is given by

$$Vi = i_a^2 R_a + \omega_m i^2 \frac{dL}{d\theta} + Li \frac{di}{dt} \text{ ----- (4)}$$

$$T = \frac{P}{\omega_m} = \frac{d\left(\frac{1}{2}Li^2\right)}{dt} \text{ ----- (5)}$$

But,  $\frac{d}{dt}\left(\frac{1}{2}Li^2\right) = \frac{1}{2}i^2 \frac{dL}{d\theta} + Li \frac{di}{dt}$

Therefore, the torque equation is given by,

$$T = \frac{1}{2}i^2 \frac{dL}{d\theta} \text{ ----- (6)}$$

The voltage equation for the generating mode of the motor is given by

$$V = i_a R_a + L \frac{di}{dt} - \omega_m i \frac{dL}{d\theta} \text{ ----- (7)}$$

And the torque produced will be

$$T = -\left(\frac{1}{2}i^2 \frac{dL}{d\theta}\right) \text{ ----- (8)}$$

The equations (1) to (8) gives the modelling equation for the switched reluctance motor. Where, the negative sign is contributed to the falling profile of inductance (negative region) with respect to the change in rotor position.

## 3. Sensor less operation using ANN

Lesser adaptability of coupling of SRM with machines through external sensors is attributed to dusty environment. Inductance and flux based sensor less operation of SRM were developed to overcome this difficulty [12]. But they faced shortcomings like one quadrant operation and limited speed range [12]. The four quadrant operation with ANN is found to be accurate in prediction of information compared to other methods [6]. Here, back propagation algorithm is used to have lesser number of iterations and higher training results [14].

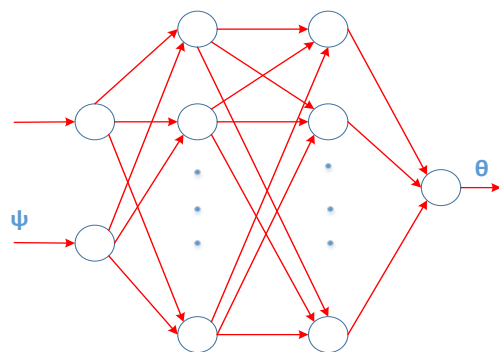


Figure 2 ANN model for position sensor

The current and flux linkage (obtained from voltage) values of the static machine characteristics ( $\psi$ -I) obtained through MagNet software are fed as input to the neural networks. The input and target data are validated and checked after training. The net file data of the rotor position is then fed to simulink file. The above figure 2 depicts the basic neural network diagram. This method is better adapted with faster 'G' prediction and eliminates the external position sensor.

#### 4. Dual mode operation of SRM

The raising region of the inductance profile of the SRM constitutes the motoring mode and the falling region constitutes the generating mode. In motoring mode, speed is the controlled parameter with the excitation given in the raising region. In generating mode, generally the output voltage is the controlled parameter with the excitation given in the falling region. If the excitation is in the optimum region, then the performance of the dual mode machine is better. Because of the non-linearity observed in the operating angle selection for different loading condition, the controller opted should be very rigid to obtain stable operation. The PID controller is replaced with sliding mode controller to avoid unpredictability caused by gain tuning for every angle obtained. Sliding mode controller is used for controlling the system to slide along a trajectory which is acceptable in its linearity range. The sliding mode control is done to set a steady state operating condition under each operating angle.

##### 4.1 Optimum angle selection in motoring mode

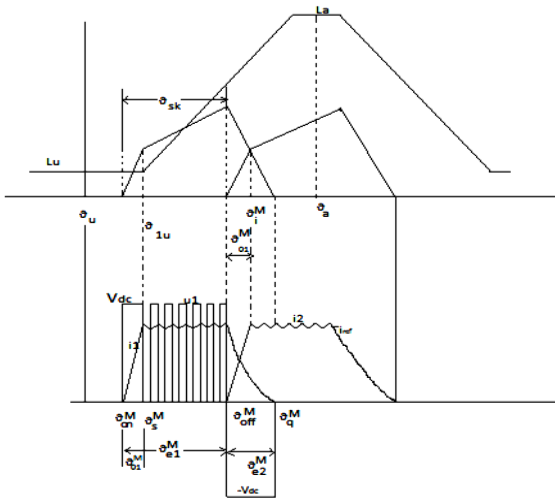


Figure 3 Motoring mode operation

The figure 3 shown below gives the current path in a single inductance curve showing the motoring mode operation. The optimum turn-on angle in

motoring mode is taken after eliminating the resistance due to the presence of inductive coils and fringing effect

$$\theta_{on}^M = \theta_{1u} - \theta_{01}^M = \theta_{1u} - \frac{L_u \cdot i_{ref} \cdot \omega_r}{V_{dc}} \quad \text{--- (9)}$$

The optimal turn-off angle in motoring mode is given by

$$\theta_{off}^M = \theta_{1u} + (2\theta_{sk} - \theta_{e2}^M) \left[ 1 - \frac{\theta_{01}^M}{\theta_{e2}^M} \right] \quad \text{--- (10)}$$

Where the equation (9) and (10) gives the optimum turn on and turn off angle estimation for the motoring mode.

##### 4.2 Optimum angle selection in generating mode

Similarly, for generating mode, the optimum turn-on angle is given by

$$\theta_{on}^G = \theta_q^G - 2 \left[ \theta_{01}^G + \theta_{sk} \left( 1 - \frac{\theta_{01}^G}{\theta_{e1}^G} \right) \right] \quad \text{--- (11)}$$

And, turn-off angle given by

$$\theta_{off}^{opt} = \theta_q^G - \theta_{01}^G \quad \text{---- (12)}$$

Where the equation (11) and (12) gives the optimum turn on and turn off angle estimation for the generating mode. The figure 4 shows the current in the generating mode operation of a switched reluctance motor. The operating angle of the SRM is equal to the stroke angle of the motor. This angle is always within the boundary limits. When it decreases below the given boundary limit, the torque obtained is reduced due to insufficient conduction period and when it crosses above the boundary limit, without producing torque winding losses only occurs. When it reaches the opposite slope then torque reversal occurs. It reduces the average torque and also stress occurs in the rotor shaft. To prevent this, the optimum region is always selected to be within the conduction region of 8/6 SRM.

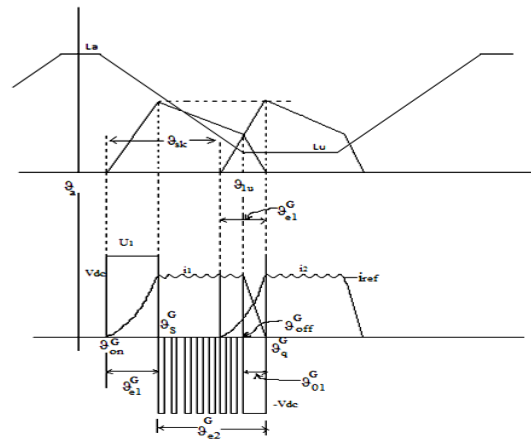


Figure 4 Generating mode operation

### 4.2.1 Conduction angle estimation

From the figure 3 & 4, it is clear that the inductance changes for every change in rotor position with respect to stator. The stroke angle corresponds to the aligned position and average torque production is maximum here. When the conduction angle is less than the stroke angle, the torque production is minimised. The conduction angle decreases with increasing load. Care is taken to ensure optimum overlapping period where average torque increases and torque ripple decreases. Dual mode operation depends upon the inductance profile slope. The operating angle is advanced by an angle of advance to obtain optimized results in the torque plot. Figure 5 shows the inductance profile of a dual mode region of switched reluctance motor.

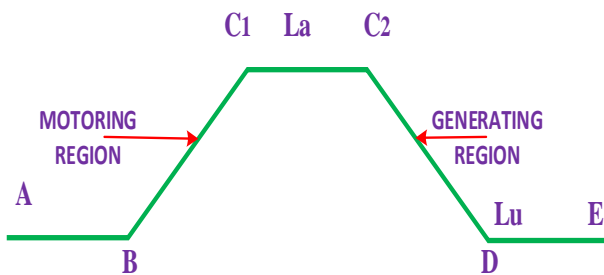


Figure 5 Inductance profile for 8/6 SRM

AB & DE - Minimum inductance region

BC1- Raising inductance region

C1C2 – Maximum inductance region

C2D- falling inductance region

$$\text{Advance angle, } \theta_{adv} = \frac{L_{min}-I_r}{V} \text{ ---- (13)}$$

The advance angle given by equation (13) is given to the turn-on angle and the turn-off angle. The turn-on angle given to energise the winding is given before the rising profile of inductance and turn-off angle to de-energise the winding is given with a period interval of fifteen degrees from the turn-on angle. Similarly, the same is done for the generating mode. This turn-on and turn-off angles are selected for obtaining better Results. This is done with the help of Particle Swarm Optimisation (MOPSO) algorithm

### 5. MOPSO algorithm

MOPSO is considered to be one of the prominent methods for finding a solution for the optimisation problems. James Kennedy and Russel Eberhart found a solution for optimisation by

selecting a search space of n dimensional in which, each particle and the dimension of their initial position vector is mentioned in randomly selected basis from the uniform distribution of most likely values. Several optimization techniques are derived based on PSO. Two techniques mainly used are Single objective PSO (SOPSO) and MOPSO. The procedure of the SOPSO is based on deriving a single objective function using the functional model; the single objective function may combine several objective functions using specified or selected weighting factors.

The objective function is optimized (either minimized or maximized) using the PSO method to obtain a single near optimal solution. On the other hand, Multi-Objective problem is finding the set of acceptable (trade-off) Optimal Solutions. This set of accepted solutions is called Pareto front. These acceptable trade-off surface or solutions give more ability to the user to make an informed decision by seeing a wide range of near optimal solutions that are near optimum from an “overall” standpoint. Single Objective (SO) optimization may ignore this trade-off viewpoint [11], which is crucial. This paper presents a new technique for finding the set of trade-off optimal solutions based on MOPSO. It can easily handle constraints of discrete nature.

The main advantages of MOPSO method are:

1. It doesn't require a priori knowledge of the relative importance of the objectives.
2. There is a set of acceptable trade-off near optimal solutions

### 5.1 Multi Objective function

$$f(x) = Ax_1 + Bx_2 \text{ ----- (14)}$$

where,

$x_1$  and  $x_2$  corresponds to maximization and minimization functions of average torque and torque ripple respectively.

A and B are weightage constants

$$\text{vel}[k] = \text{vel}[k] + c_1 * \text{rand}[k] * (\text{prsnl best}[k] - \text{prsnl}[k]) + c_2 * \text{rand}[k] * (\text{glbl best}[k] - \text{prsnl}[k]) \text{ ----- (15)}$$

$$\text{prsnl}[k] = \text{prsnl}[k] + \text{vel}[k] \text{ -----(16)}$$

For best results the cognitive parameter c1 and social parameter c2 of the equations (14), (15), (16) are selected to be 1.4. The initial population is set to be 30 and no of iterations is fixed at 100.

The table 1 shows the values obtained in the MOPSO algorithm for various Ton and Toff.

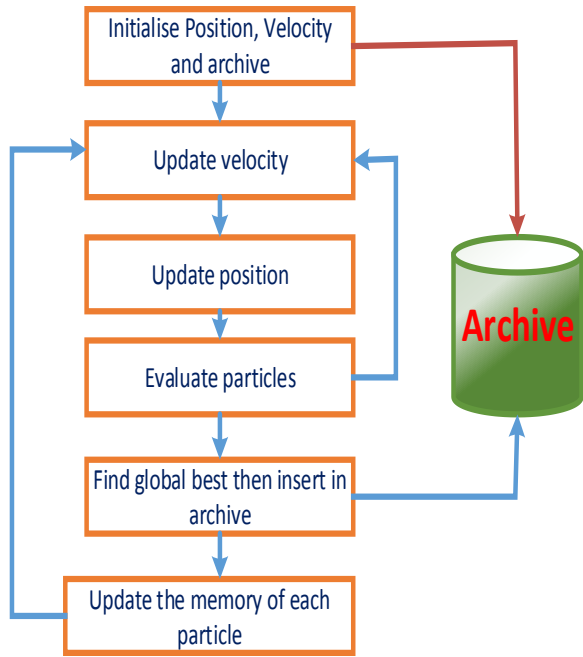


Figure 6 Flow chart of the MOPSO search algorithm

### 5.2 Main Constraints

The main constraints to be the turn off angle should be fifteen degrees from the turn on angle.

<b>MOPSO</b>			
<b>Ton</b>	<b>Toff</b>	<b>Tavg</b>	<b>Trip</b>
5.78	20.78	1.42	0.217
5.62	20.62	1.43	0.218
5.76	20.76	1.41	0.219
<b>5.01</b>	<b>20.01</b>	<b>1.50</b>	<b>0.199</b>
5.56	20.56	1.44	0.230
5.54	20.54	1.42	0.240
5.59	20.59	1.43	0.210
5.46	20.46	1.42	0.223
5.29	20.29	1.45	0.232
5.44	20.44	1.46	0.223

Table 1 Set of Solutions based on MOPSO

$$\theta_{off} - \theta_{on} = \frac{Ns - Nr}{NrNs} * 360^\circ \text{ ----- (17)}$$

Where

$$T_{on} \geq 0^\circ, T_{off} \leq 30^\circ$$

The table 2 shows the comparison between the SOPSO and MOPSO and shows an increase in the Average torque with minimum Torque ripple values.

	<b>SOPSO Tavg</b>	<b>SOPSO Tripple</b>	<b>MOPSO Tavg</b>	<b>MOPSO Tripple</b>
<b>Max</b>	1.459	0.211	1.468	0.199
<b>STDEV</b>	0.000149	0.000198	0.00018	0.000299
<b>min</b>	1.426	0.201	1.443	0.175
<b>Mean</b>	1.454	0.193	1.466	0.186

Table 2 Comparison of SOPSO & MOPSO Results

### 6. Simulation results

Figure 7 shows the flux linkage and the corresponding current variations under dynamic conditions of switched reluctance machine. Figure 8 shows the ANN training process of the position information based on flux linkage and current samples. After the training the net file traces the position of the rotor very closely, so based on the net file position sensor is removed. Figure 9 portraits the motoring mode operation with MOPSO based Turn On and Turn Off angle of 5.01° and 20.01°. Figure 10 portraits the Generating mode operation with MOPSO based Turn On and Turn Off angle of 35.01° and 50.01°.

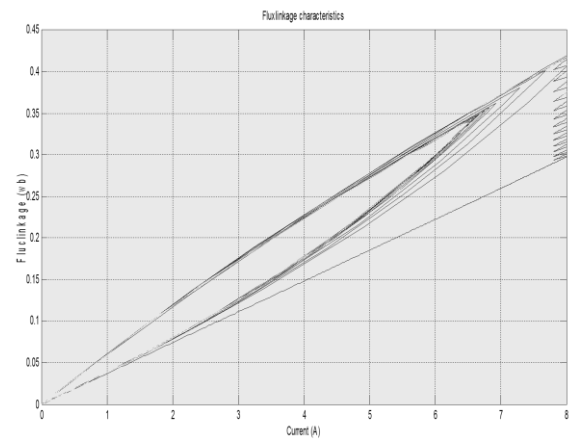


Figure. 7 Flux linkage vs Current

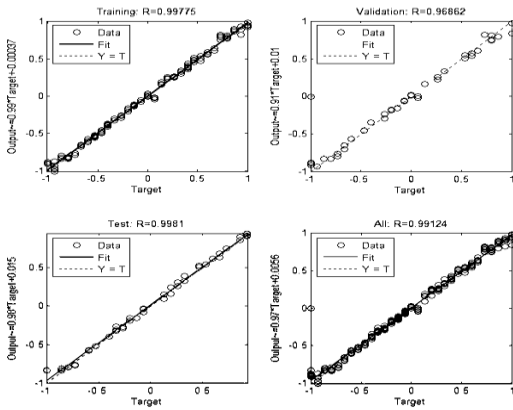


Figure. 8 ANN based training for prediction of theta

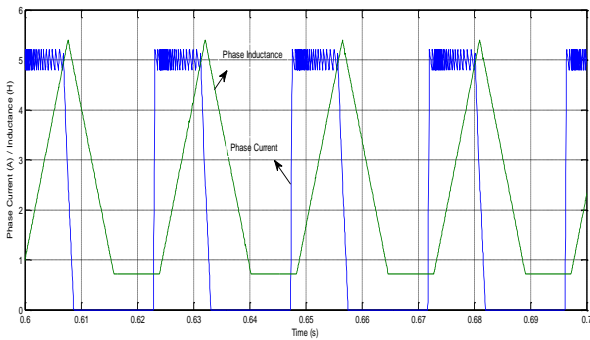


Figure 9 Motoring angle switching in MOPSO angle

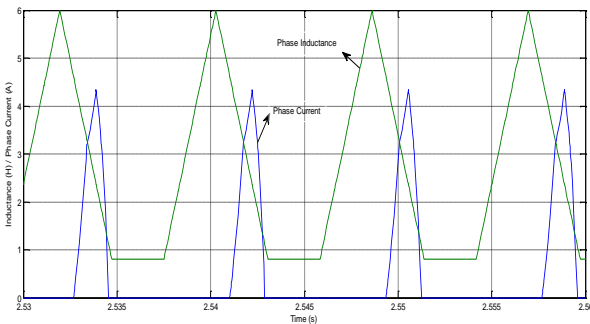


Figure 10 Generating angle switching in MOPSO angle

## 7. Experimentation and Results



Figure 11 Experimental Setup of 8/6 SRM

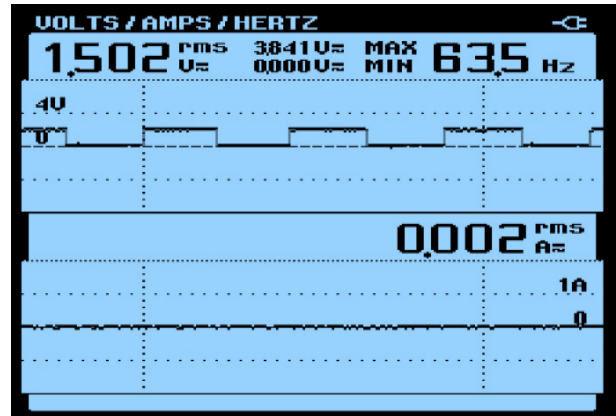


Figure 12 Position signals from Optical encoder

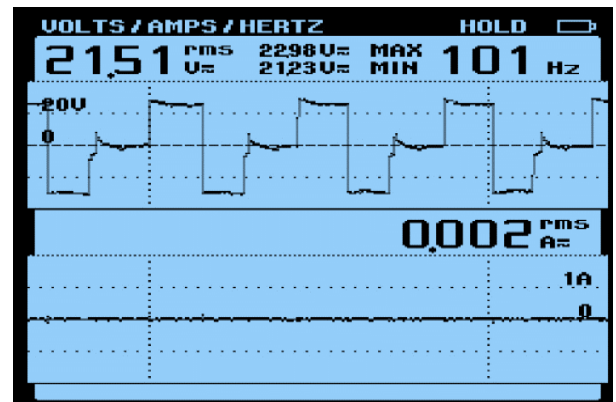


Figure 13 Voltage and current waveforms for optimum angle

In the hardware implementation sensor based fixed angle setup is used. The operating angle is chosen from the MATLAB simulation based MOPSO optimized results. Turn on angle is 50 and turn off angle is 200. Figure 11 show the experimental setup of 8/6 switched reluctance motor. Figure 12 and 13 shows Position signals from Optical encoder and the voltage and current switching waveforms at MOPSO based optimum operating angle.

## 8. CONCLUSION

The dual mode operation of a Switched Reluctance Motor with a sensor less scheme is implemented using MATLAB/SIMULINK platform and the optimised angles are generated by a MOPSO algorithm. The optimum switching angles are used for converter switching, the average output torque value is increased, and the corresponding torque ripple is decreased in the considerable level. The results obtained are validated in the dual mode of operation.

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