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Research Article

Optimum Change of Switching Angles on Switched Reluctance Motor Performance

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Abstract

This paper presents the effect of change the switching angles values on the operation of switched reluctance motor (SRM) at no-load in aircraft applications. Turn-on θ_{on} and turn-off θ_{off}, angles are the two switching angles that play a major role in deciding whether SRM develops positive or negative, high or low electromagnetic torque. These switching angles are considered as the main excitation parameters in SRM performance and also they support the most efficient operation through producing high value of total torque per ampere. The SRM, converter, and control system are modeled in Simulink model to demonstrate the drive system operation using MATLAB/SIMULINK software package. The simulated performance of SRM drive system is presented to analyze the effect of different switching angles on no-load performance of speed, current and torque. An optimum of turn-on and turn-off angles that ensures stable at no-load operation is recommended.

Keywords: *SRM, switching/firing angles, turn-on, turn-off, advance turn-on, retard turn-off, comparator*

1. Introduction

The torque of SRM is produced in pulsating form due to the discrete nature of torque production mechanism. The SRM stator phases are independently controlled and the total electromagnetic torque is the sum of the torques generated by each of the machine phases. Torque pulsations are stronger at the commutation intervals because the two adjacent phases produce additive torques. Therefore, the switching angle control or field orientation control can be used to control the SRM drive system. This control strategy is based on controlling the values of the turn-on angle, the turn-off angle, and the interval between these angles known as the dwell angle (Kiran Srivastava, *et al*, 2011). Using this control strategy will minimize the torque ripple and maximize the machine efficiency and also maximize the ratio of the average torque to RMS phase current (Kiran Srivastava, *et al*, 2011), (Yilmaz Sozer, *et al*, 2003). So, the angle control strategy is used to control the dwell angle and input voltage instantaneously in order to obtain precise speed control with high efficiency. In the real control system, control of the switching angles can be realized by simple feedback circuit using detecting position sensor on the motor shaft. The feedback signal which is proportional to the phase detector is used to regulate the instantaneous applied voltage (Jin-Woo Ahn, 2011).

As the motor speed increases, the back-emf becomes significant. It is necessary to advance the turn-on angle or late/retard the turn-off angle in order to reach the reference current before the poles overlap. To build up the current effectively with a voltage source, an advance switching is needed before the machine poles meet, the turn-on angle is advanced so that the phase current reach its reference value on the angle at which the poles start to overlap (Jin-Woo Ahn, 2011), (Catalin and Ronnie, 2011), (Mademlis and Kioskeridis, 2003).

One reason of obtaining torque ripple in SRM drive is the negative torque due to the tail current. The output torque of a machine phase is changed by the inductance slope. If the phase current is extended to the opposite torque region, the current produces the opposite torque. In the high speed condition, the phase current is not extinguished in the same torque region, and the extended tail current produces negative torque. The turn-off angle for smooth operation is selected at the rotor position that stator and rotor pole corners complete overlap. When the turn-off angle is controlled to remove the tail current, negative torque can be removed. If the turn-off angle is retarded to reduce the tail current, the effective torque region is much increased with high efficiency and high output torque per ampere (Jin-Woo Ahn, 2011), (Mademlis and Kioskeridis, 2003), (Dong-Hee, *et al*, 2011).

This paper introduces phase current advance and phase current retard via changing the value of switching angles of SRM for obtaining most precise operation at no-load.

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2. Components of SRM drive system

The basic elements of the SRM drive system are shown in Fig. 1. These elements are DC voltage source, asymmetric DC-DC converter, 3-ph 6/4 SRM, position sensor, and comparator. The DC voltage source has a value of U = 220V. The asymmetric converter as mentioned in (Samia, *et al*, 2013) is a power supply unit that follows the commands of the comparator to energize each phase of the motor at the appropriate times. It is required to activate and commutate the motor phases. Therefore, it does not only deliver energy to an electronic device from an electrical outlet, it also regulates the current to meet specific device requirements and should have the ability of regulation to provide increasing or decreasing of phase current. The SRM parameters are shown in Appendix A. The position sensor detects the rotor position because phase excitation pulses need to be properly synchronized to the rising region of the inductance profile for motoring operation. The comparator regulates the motor performance via comparing the measured rotor position θ, switching turn-on angle θ_{on}, and switching turn-off angle θ_{off} (Ahmed Abdel-Hafez, 2012), (Keunsoo Ha, 2008), (Torsten, 2008). Where, the comparator can be implemented experimentally using a programmed computer connected to a controller that follows the commands of the simulated program in this computer (Wenzhe Lu, 2005).

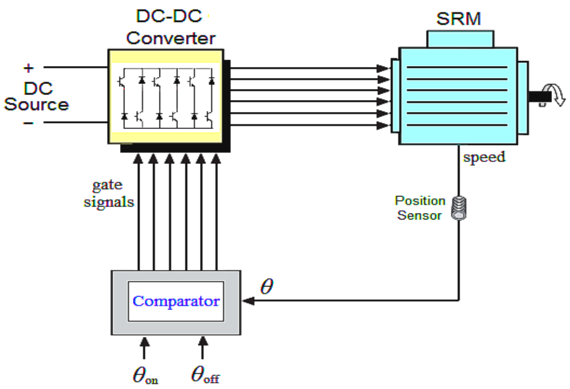

Fig. 1 Three-ph 6/4 SRM drive system

The switching/firing angles have a major role in the SRM operation. They develop a positive or negative, a low or high electromagnetic torque for the SRM and also are function of the motor speed and change with acceleration, so the driver requires a sophisticated and complex digital controller which named as a switching angle controller that is considered as the main part of the comparator (Hamid Ehsan, 2004). The firing angles may not be synchronized with their respective positions without using the switching angle comparator. It is seen that the role of the switching angle controller is to regulate the angles at which excitation of phases is achieved, and so allowing the rotor to continuously rotate, producing torque in accordance with the load being applied. The torque transition from one phase to the other is also dependent upon the controller. By using the correct firing angles, these torque transitions are implemented smoothly, resulting in a smooth operation of the motor.

The optimum performance of SRM depends upon the appropriate amount of the currents relative to rotor position. At controlling the motor; as the current passes through one phase, the torque is generated by the tendency of the rotor to align with the excited stator pole. The direction of the torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flowing through the phase winding. Continuous torque can be produced by synchronizing each phase's excitation with the rotor position. The amount of current flowing through motor windings is controlled by switching on and off the motor phases by the power electronic switches of the DC-DC converter.

3. Simulink model of SRM drive system

The firing angles are changes by means of software to obtain the best values for these angles. The Simulink block control diagram at using switching angle control for 3-ph 6/4 SRM is shown in Fig. 2. The simulation program uses MATLAB/SIMULINK software package. The data required for this motor in the following block control diagram obtained from Appendix (A). The simulation results obtained at no-load of the motor. As shown in Fig. 2, the motor characteristics that obtained versus rotor position are phase inductance, phase current, total torque, and motor speed. Also, average characteristics will be obtained for make easy comparison between phase advance and phase retard.

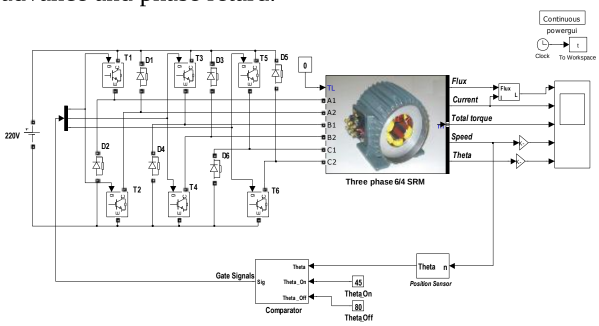

Fig. 2 Simulink model using angle control for 3-ph 6/4 SRM at no-load

4. Advance switching turn-on angle

The principle of increasing advance of the turn-on angle (*i.e*, decrease value of the turn-on angle) is to increase the average motor total current as shown in Fig. 3. This figure shows the steady state (after one plus one-fourth complete cycle, *i.e* 490^{o}) phase current at using constant turn-on angle θ_{on}= 40^{o} and constant turn-off angle θ_{off}= 70^{o}. An advance for turn-on angle by 2^{o} is used. For example, the phase current I_A has three cases: the case of solid line; the phase has no advance where the rotor position is 490^{o} means that θ_{on}= 40^{o}, the case of dashed line; the phase has advance by 2^{o} where the rotor position is 488^{o} means that θ_{on}= 38^{o}, and the case of doted line; the phase has advance by 4^{o} where the rotor position is 486^{o} means that θ_{on}= 36^{o}. Then, when we see deeply, the phases current increases as the turn-on angle is advanced further, also, the motor total current increases (but more increase of current is undesirable) to produce increase in the average total torque as shown in Fig. 4 and Fig. 5 respectively.

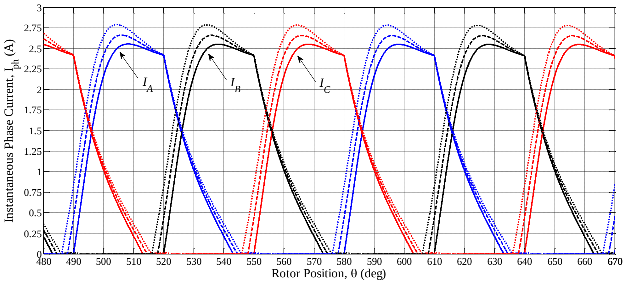

Fig. 3 Instantaneous motor phases current versus rotor position for advance turn-on

As shown in Fig. 3, the phase current increases with increasing the advance turn-on, but, the limit of increasing for phase current is possible for the current drawn by the motor from the source to be not greater than maximum allowable current. This maximum allowable current is about 1.25 of the rated source current.

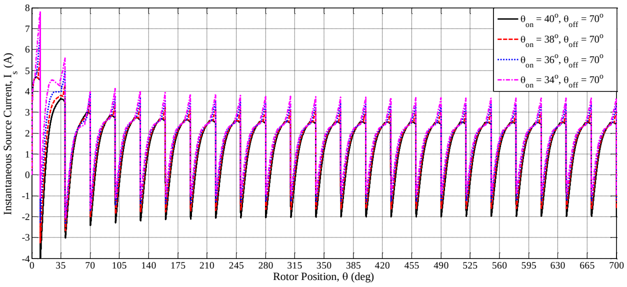

Fig. 4 Instantaneous source current versus rotor position for advance turn-on

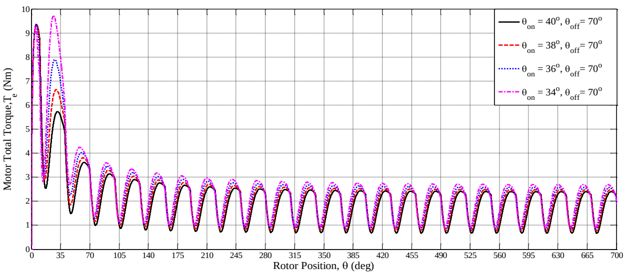

Fig. 5 Motor total torque versus rotor position for advance turn-on

5. Retard switching turn-off angle

On the other hand, the principle of increasing delay or retard the turn-off angle (*i.e,* increase value of the turn-off angle) is to increase the commutation period between switching angles for increasing the average motor total torque as shown in Fig. 6. This figure shows the steady state (after one plus one-fourth complete cycle, *i.e* 480^o) phase current has constant turn-on angle θ_{on}= 40^o and constant turn-off angle θ_{off}= 70^o. A retard for turn-off angle by 2^o is used. For example, the phase current I_A has three cases: the case of solid line; the phase has no delay where the rotor position is 520^o means that θ_{off}= 70^o, the case of dashed line; the phase has delay by 2^o where the rotor position is 522^o means that θ_{off}= 72^o, and the case of doted line; the phase has delay by 4^o where the rotor position is 524^o means that θ_{off}= 74^o. Then, when we see deeply, the phases current increases as the turn-off angle is delayed or retard, also, the motor total current increases (but more increase of current is undesirable) to produce increase in the average total torque as shown in Fig. 7 and Fig. 8 respectively. As shown in Fig. 6; the phase current increases with increasing the retard or delay the turn-off angle. We must note that there is allowable range for change the value of turn-on and turn-off angles, unless, the motor operation not responds to this change.

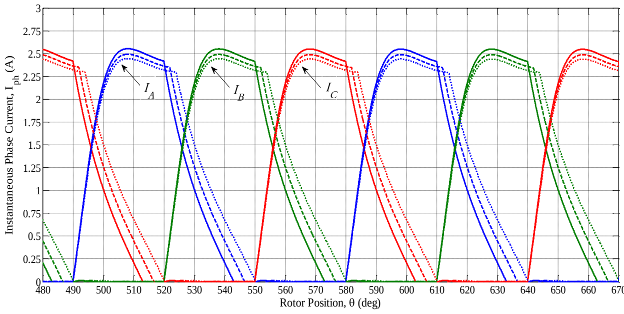

Fig. 6 Instantaneous motor phases current versus rotor position for retard turn-off

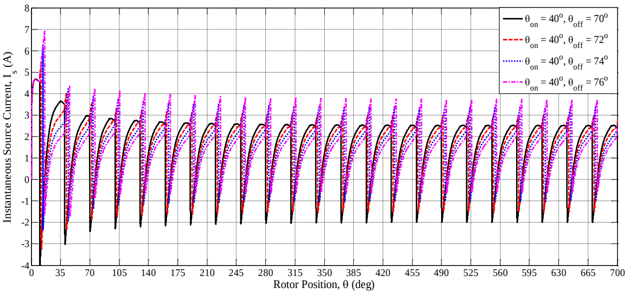

Fig. 7 Instantaneous source current versus rotor position for retard turn-off

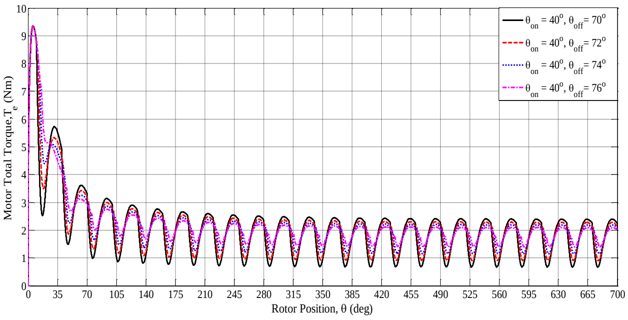

Fig. 8 Motor total torque versus rotor position for retard turn-off

6. Average motor characteristics

In this part the advance turn-on and the retard turn-off for motor phases current will be studied to show that which/all of them is preferred to obtain better torque per ampere and more efficient operation.

6.1 Average characteristics for advance turn-on

As shown in Fig. 9; at constant turn-off angle (say θ_{off}= 70^o), as the switching turn-on angle decreases, the average source current increases. Also as shown in Fig. 10; at constant turn-off angle (say θ_{off}= 70^o) as the switching turn-on angle decreases, the average total torque increases. In other words, for constant turn-off angle; the average source current or average total torque increases as the advance of the turn-on angle increases.

One of the main important characteristics of SRM is the variation of the total torque per ampere with respect to the change in the switching turn-on angle. We obtained from Fig. 9 and Fig. 10 that more advancing of turn-on angle produces large increase in the average source current and small increase in the average total torque, so, this will lead to decrease in the average total torque per ampere as shown in Fig. 11. Also, as shown in Fig. 12, increasing advance of θ_{on} leads to increases of the motor speed.

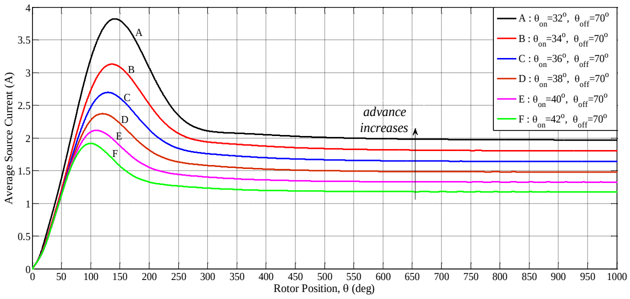

Fig. 9 Average source current versus rotor position for advance turn-on

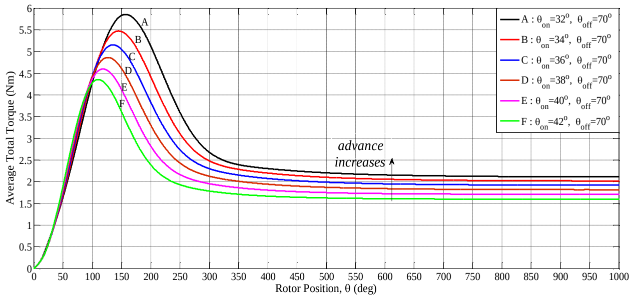

Fig. 10 Average total torque versus rotor position for advance turn-on

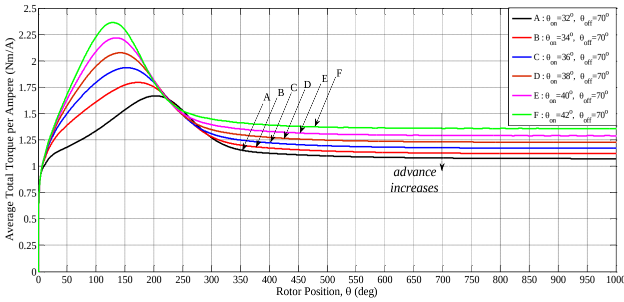

Fig. 11 Average total torque per ampere versus rotor position for advance turn-on

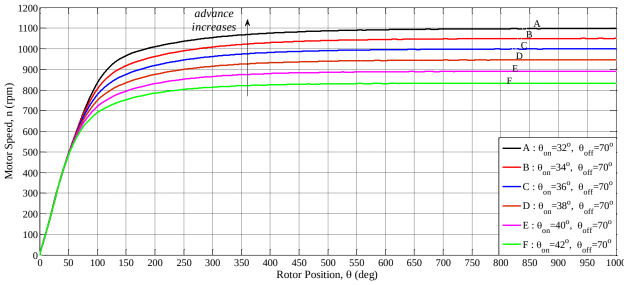

Fig. 12 Motor speed versus rotor position for advance turn-on

6.2 Average characteristics for retard turn-off

As appeared in Fig. 13; for constant turn-on angle (say θ_{on}= 40^o), as the firing turn-off angle increases, the average source current increases. This means that average source current increases as retard of the turn-off angle increases. Also the average total torque increases as retard of the turn-off angle increases, as shown in Fig. 14.

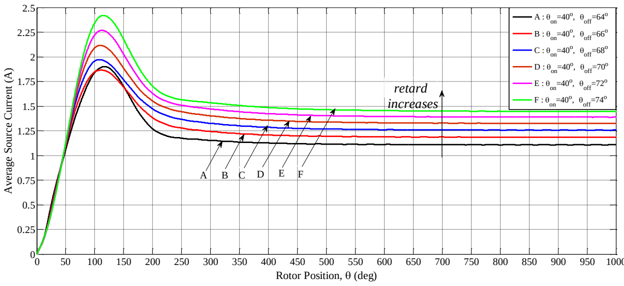

Fig. 13 Average source current versus rotor position for retard turn-off

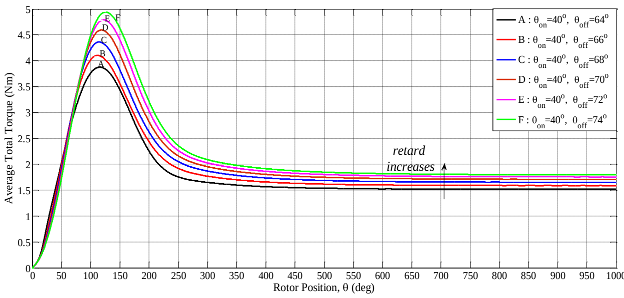

Fig. 14 Average total torque versus rotor position for retard turn-off

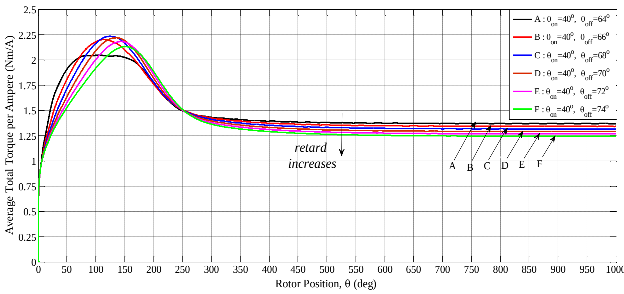

Fig. 15 Average torque per ampere versus rotor position for retard turn-off

As shown in Fig. 13 and Fig. 14; for constant turn-on angle (say θ_{on}= 40^o), as retard of the turn-off angle increases, large increase in the average source current and small increase in the average total torque is produced, so, this will lead to decrease in the average total torque per ampere as presented in Fig. 15. Also, increasing retard of θ_{off} leads to increases of the motor speed, as shown in Fig. 16.

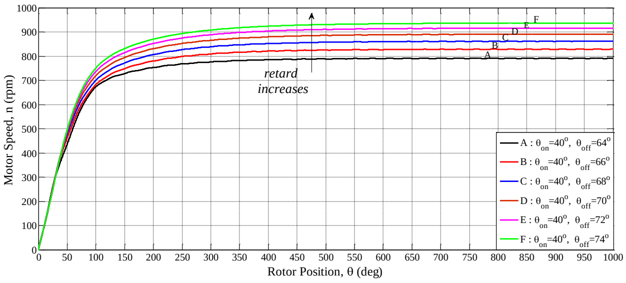

Fig. 16 Average motor speed versus rotor position for retard turn-off

In order to the motor phases respond to drawn current from source to drive the SRM, There is maximum allowable range of θ_{on} and θ_{off} for 3-ph 6/4 SRM. The motor average characteristics for this range will be stored in the following tables from Table 1 through Table 4. These characteristics obtained at steady state speed by apply rated source voltage of 220V.

6.3 Allowable range of advance turn-on & retard turn-off

The average source current is shown in Table 1 at different values of turn-on and turn-off angles to obtain the optimum performance operation for the drive at no load; where the minimum limit and the maximum limit of switching angles presented in the Table. From Table 1; adjustment of the switching angles is presented in order to get a minimum average source current of 0.152A at turn-on angle of 58^o and turn-off angle of 64^o. But in Table 2; the maximum average total torque is 2.224Nm at turn-on angle of 32^o and turn-off angle of 78^o, but this value of torque not present optimum machine performance because the optimum performance depends on getting maximum torque per ampere as in Table 3. The motor speed at all switching angles is presented in Table 4.

Table 1 The average source current in (A)

θ_{on} \ θ_{off}	64°	66°	68°	70°	72°	74°	76°	78°	80°	82°
32°	1.735	1.819	1.896	1.967	2.031	2.087	2.136	2.179	2.200	2.180
34°	1.572	1.655	1.731	1.801	1.865	1.922	1.972	2.015	2.051	2.075
36°	1.413	1.493	1.568	1.638	1.702	1.760	1.811	1.855	1.892	1.923
38°	1.257	1.335	1.410	1.479	1.543	1.601	1.653	1.699	1.739	1.772
40°	1.107	1.183	1.256	1.324	1.388	1.446	1.500	1.546	1.588	1.624
42°	0.964	1.037	1.110	1.177	1.238	1.298	1.351	1.399	1.442	1.481
44°	0.828	0.901	0.968	1.034	1.098	1.155	1.209	1.259	1.304	1.345
46°	0.701	0.772	0.840	0.903	0.963	1.021	1.076	1.125	1.172	1.216
48°	0.582	0.650	0.716	0.780	0.839	0.897	0.951	1.002	1.049	1.094
50°	0.475	0.542	0.604	0.667	0.726	0.780	0.835	0.886	0.935	0.982
52°	0.378	0.440	0.502	0.562	0.619	0.675	0.726	0.779	0.829	0.877
54°	0.292	0.351	0.409	0.467	0.522	0.578	0.631	0.682	0.731	0.779
56°	0.220	0.271	0.327	0.381	0.436	0.489	0.542	0.591	0.643	0.691
58°	0.152	0.200	0.253	0.306	0.357	0.409	0.460	0.510	0.559	0.609

Table 2 The average total torque in (Nm)

θ_{on} \ θ_{off}	64°	66°	68°	70°	72°	74°	76°	78°	80°	82°
32°	1.921	1.992	2.053	2.106	2.149	2.184	2.210	2.224	2.219	2.179
34°	1.827	1.899	1.960	2.013	2.058	2.094	2.121	2.137	2.141	2.127
36°	1.729	1.800	1.862	1.916	1.962	2.000	2.028	2.046	2.052	2.043
38°	1.625	1.696	1.759	1.813	1.543	1.900	1.930	1.950	1.959	1.953
40°	1.515	1.587	1.652	1.707	1.755	1.446	1.828	1.850	1.861	1.858
42°	1.401	1.475	1.540	1.597	1.646	1.688	1.722	1.747	1.760	1.760
44°	1.283	1.359	1.424	1.483	1.534	1.578	1.614	1.641	1.657	1.659
46°	1.162	1.238	1.307	1.368	1.421	1.466	1.505	1.534	1.552	1.558
48°	1.037	1.118	1.189	1.251	1.306	1.355	1.396	1.427	1.448	1.456
50°	0.912	0.997	1.070	1.136	1.194	1.244	1.286	1.321	1.344	1.355
52°	0.786	0.874	0.952	1.020	1.081	1.134	1.179	1.216	1.242	1.256
54°	0.662	0.752	0.834	0.907	0.970	1.027	1.074	1.114	1.142	1.160
56°	0.538	0.632	0.717	0.793	0.861	0.921	0.971	1.014	1.046	1.066
58°	0.412	0.508	0.602	0.683	0.754	0.817	0.871	0.917	0.952	0.975

Table 3 The average total torque per ampere in (Nm/A)

θ_{on} \ θ_{off}	64°	66°	68°	70°	72°	74°	76°	78°	80°	82°
32°	1.107	1.095	1.083	1.070	1.058	1.046	1.035	1.021	1.009	1.000
34°	1.162	1.147	1.132	1.118	1.103	1.089	1.076	1.061	1.044	1.025
36°	1.224	1.206	1.188	1.170	1.153	1.136	1.120	1.103	1.085	1.062
38°	1.293	1.270	1.248	1.226	1.000	1.187	1.168	1.148	1.127	1.102
40°	1.369	1.342	1.315	1.289	1.264	1.000	1.219	1.197	1.172	1.144
42°	1.453	1.422	1.387	1.357	1.330	1.300	1.275	1.249	1.221	1.188
44°	1.550	1.508	1.471	1.434	1.397	1.366	1.335	1.303	1.271	1.233
46°	1.658	1.604	1.556	1.515	1.476	1.436	1.399	1.364	1.324	1.281
48°	1.782	1.720	1.661	1.604	1.557	1.511	1.468	1.424	1.380	1.331
50°	1.920	1.839	1.772	1.703	1.645	1.595	1.540	1.491	1.437	1.380
52°	2.079	1.986	1.896	1.815	1.746	1.680	1.624	1.561	1.498	1.432
54°	2.267	2.142	2.039	1.942	1.858	1.777	1.702	1.633	1.562	1.489
56°	2.445	2.332	2.193	2.081	1.975	1.883	1.792	1.716	1.627	1.543
58°	2.711	2.540	2.379	2.232	2.112	1.998	1.893	1.798	1.703	1.601

Table 4 The average motor speed in (rpm)

θ_{on} \ θ_{off}	64°	66°	68°	70°	72°	74°	76°	78°	80°	82°
32°	1002	1039	1071	1099	1121	1140	1153	1161	1158	1137
34°	953	991	1022	1051	1074	1093	1107	1115	1117	1110
36°	902	939	971	1000	1024	1043	1058	1068	1071	1066
38°	848	885	918	946	971	991	1007	1018	1022	1019
40°	791	828	862	891	916	937	954	965	971	970
42°	731	770	803	834	859	881	899	911	919	919
44°	669	710	744	773	801	824	842	856	864	866
46°	607	647	682	715	742	766	785	801	810	813
48°	541	584	621	653	683	708	729	745	756	760
50°	476	521	558	594	624	649	671	689	702	707
52°	410	457	498	534	565	592	616	635	649	656
54°	345	392	436	474	507	537	562	582	597	605
56°	283	331	375	414	450	481	508	530	547	556
58°	214	269	315	356	394	427	454	478	497	509

Conclusions

This paper presents the study on determination of a unique of turn-on and turn-off angles that gives optimum performance of the SRM during no-load starting. At steady state, for constant turn-off angle, if the advance of the turn-on angle increases (*i.e*, decreasing value of θ_{on}), then the average source current, the average total torque and the average total torque per ampere are directly proportional to advance of turn-on angle. The motor speed is directly proportional to advance of turn-on angle.
And at steady state, for constant turn-on angle; if the retard of the turn-off angle increases (*i.e*, increasing value of θ_{off}), then the average source current, the average total torque and the average total torque per ampere are directly proportional to retard of turn-off angle. The motor speed is directly proportional to retard of turn-off angle

Appendix A: Motor Parameters

Number of motor phases	: K = 3
Number of stator poles	: N_S = 6
Number of rotor poles	: N_R = 4
Stator pole arc (mech. deg.)	: β_S = 40º
Rotor pole arc (mech. deg.)	: β_R = 45º
DC voltage rating	: U = 220 V
Stator phase resistance	: R = 17 Ω
Aligned inductance	: L_{al} = 0.605 H
Unaligned inductance	: L_{ul} = 0.155 H
Inertia constant	: J = 0.0013 Kg.m^2
Viscous friction coefficient	: B = 0.0183 N.m.Sec^2
Rated speed	: n_r = 1000 rpm
Rated phase current	: I_r = 3 A
Rated torque	: T_e = 1 Nm
Rotor pole arc (mech. deg.)	: θ_r = 30º

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