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New Development in the Performance Improvement Synchronous Motor

V. Chandrasekaran[1], D. Nagarajan[2], B. Nagaraj[3]

[1]Department of Electrical and Electronics Engineering, Sri Eshwar College of Engineering, Coimbatore, India
[2]Department of Electrical and Electronics Engineering, Karpagam College of Engineering, Coimbatore, India
[3]Department of Electronics and Communication Engineering, Karpagam College of Engineering, Coimbatore, India
Email: vcskit@gmail.com

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Abstract

Synchronous machines are dedicated to the specific application. They are generally employed in rolling mills, pumps, fans, and compressors like reprobating and centrifugal drives, pulp and paper processing, water treatment, mining, and in cement industries. As a synchronous motor, the performance is reduced for the given excitation while the load increases. When operated as synchronous generators, both power loads and lighting loads depend on the output from the armature winding. This paper presents an alternative choice in which by providing an additional winding in the stationary armature, when operated as a Double Winding Synchronous Motor (DWSyM), it becomes possible to operate in maximum power factor by adjusting the loads on both the stator windings. When operated as conventional motor, for the load current of 3.5 A, the efficiency is 55% and power factor is 0.55, for the same excitation when second winding is connected to a load current of 1 A, the efficiency is improved to 77.6% and power factor is improved to 0.66. The main focus of this machine is to improve the performance of the machine for the reduced excitation and minimum load. For the reduced excitation, the performance can be improved by loading both the windings. While operated as Double Winding Synchronous Generator (DWSyG), two stator outputs are available which help to separate the power and lighting circuits. Hence, interruption in the lighting circuit can be limited, this machine can be considered as Twin generator.

Keywords

Double Winding Synchronous Motor (DWSyM), Double Winding Synchronous Generator (DWSyG), Performance Improvement, Energy Conservation, Twin Generator

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1. Introduction

Synchronous generators are the major source of electrical power conversion to meet the existing demands. The excitation of synchronous generators is one of the main challenges in the power system. The field windings are energized through an Automatic Voltage Regulator (AVR) with control and measuring units which provides satisfactory operation with little disturbances like power swing. This can be overcome using additional control over the excitation system [1] [2]. Leakage flux can be reduced with double disc generator and by providing Permanent Magnets and field coils on the shaft [3] [4]. In order to eliminate the need of brushes, a three-phase rotor winding provides excitation current even from standstill. The control of the excitation current at different speeds is also made possible. Brushless excitation system and static excitation system are two methods employed to feed the field winding of synchronous machine [5] [6]. Double winding in the stator was recommended in the year 1930 for turbine alternators. In this machine, when stator is energized, the revolving magnetic field established in the air gap is used to develop three-phase EMF in one set of winding at the same time, and a mechanical power is also developed as conventional induction motor [7]. For energy conservation, induction machine was suggested with two sets of three-phase windings and these windings are energized based on shaft load thereby eddy current loss and copper losses are reduced. Improvement in the power factor is also observed due to this type of excitation [8]. Dual stator winding machines may be considered for various motor and generating applications with more flexible energy conversion. Both armature windings are of the same pole number, which may cause circulating currents due to unbalanced power supply [9]. Dual winding design modification can be carried out during rewinding process to reduce the cost of the machine in align with annual energy consumed [10]. From the above references, the various excitation methods of synchronous generators are studied. Energy conservation machines consist of two sets of three-phase windings in its stator. Based on the load demand, the windings are energized to minimize the losses.

In this paper an attempt is made in the design of synchronous machine in which armature consists of two set of three-phase windings. When operated as synchronous motor, the power factor and efficiency are slightly decreased for a given excitation. In the suggested model, since armature has two windings, a three-phase EMF is developed in the second set of winding, by connecting an external electrical load the overall performance of the motor is improved for the given excitation. While operated as synchronous generator, due to the two windings in the stator, the power and lighting loads can be separated, due to which the interruption to the lighting circuit can be minimized. In this mode of operation, the machine can be considered as “Twin Generator” due to two distinct three-phase outputs.

2. Constructional Details

2.1. Construction of Armature

Stationary armature rotating field type of synchronous machine is presented in this discussion. The armature consists two double layers three-phase winding distributed in the stator core. Rotating field consists of excitation winding and slip ring arrangement. For the maximum utilization of developed power, it is suggested that, the two set of windings may be arranged with different phase angles, however for the optimum power output, shaft angle of zero degree or 60 degree may be considered. In the proposed machine zero degree displacement is provided between the two sets of windings. The stator windings of a double winding motor can be arranged with different shift angles between them. In double winding induction motor, shift angle of 60 degrees or zero degrees are the best choice [11]. For As a proof for the discussion, a 3 kW, 415 V, 4-pole, 3-phase Double Winding Synchronous Motor (DWSyM) has been considered and tested.

2.2. Design Details

Armature of DWSyM consists of two sets of three-phase windings. By adjusting electrical and mechanical loads, current flow in the machine is maintained such a way that the machine does not exceed its thermal capacity. This of design is suitable for lower capacity synchronous machines. For conventional three-phase winding the slot utility factor is around 25% where is in DWSyM it is about 43.3% which ensures the better utility of slots. The armature and field construction of DWSyM is shown in **Figure 1**.

Design details of DWSyM

Armature design

Number of poles = 4

Figure 1. Double winding synchronous motor.

Synchronous speed = 1500 rpm
Diameter of the core = 0.139 m
Length of the core = 0.11 m
Number of turns per phase = 215
Electrical loading = 18,000 A/m^2
Magnetic loading = 0.44 wb/m^2
Stator consists of two sets of double layers windings with the same number of turns and cross sectional area.
Current density chosen is 6.0 A/mm^2.
Field Design
Filed MMF = 1254 A
Excitation voltage = 60 V
Number of turns = 1127
Current density = 6.0 A/mm^2

3. Experimental Investigations

The current and flux density waveforms help to calculate iron losses of electrical machine. Numerical method using finite element analysis is used for calculation. This type of testing is suitable for synchronous and DC machines [12]. Control strategy with vector controller helps to compensate core loss component ripple measurement [13]. The testing arrangement of DWSyM is shown in **Figure 2**. Experimental set up shows the mechanical loading through brake drum arrangement and electrical loading with lamp load and loading rheostats. The main focus of the testing is to observe the performance of DWSyM for the various excitation conditions by loading both the windings.

Initially load test was carried out using brake drum arrangement for the various filed currents while second set of winding is left free. Torque, mechanical output and efficiency are observed. Another set of testing was carried out in which for different excitations in which second winding is also loaded using loading rheostat and lamp loads, the performance of the machine is observed.

Table 1 shows the reading observed with rated field excitation with 60 V and field current of 0.85 A. It is observed that the maximum power factor is 0.75, efficiency is 78% for the load current of 6 A. The minimum power factor is observed as 0.64 for the load current of 3 A, the efficiency of the machine for this load is 83%. The efficiency and power factor characteristics are shown in **Figure 3** & **Figure 4**.

Table 2 shows the reading observed with rated field excitation with 50 V and field current of 0.72 A. It is observed that the maximum power factor is 0.66 and efficiency is 84.3% for the load current of 4.5 A. The minimum power factor is observed as 0.5 for the load current of 3 A, the efficiency of the machine for this load is 83%. The efficiency and power factor characteristics are shown in **Figure 5** & **Figure 6**. When the excitation is reduced, it is observed that the power factor of the machine decreases.

Figure 2. Experimental setup.

Table 1. Conventional brake test with excitation 60 V, field current 0.85 A.

Input Voltage (V)	Line Current (A)	Input Power (W)	Output Power (W)	% Efficiency	Power Factor
415	2.4	240	0	0	0.13
415	3.0	1400	1162	83.0	0.64
415	3.5	1840	1540	83.6	0.73
415	4.0	2080	1727	83.0	0.72
415	4.5	2400	2025	84.3	0.74
415	5.0	2680	2250	83.1	0.74
415	5.5	2840	2371	83.4	0.71
415	6.0	3240	2556	78.0	0.75

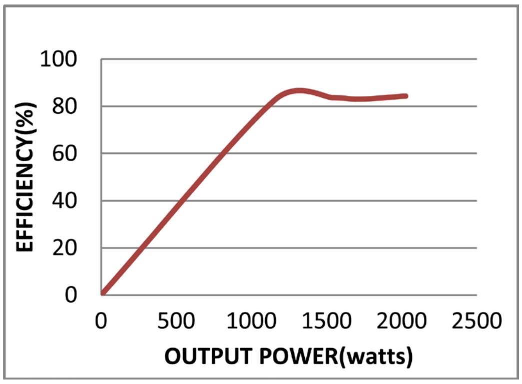

Figure 3. Efficiency characteristics.

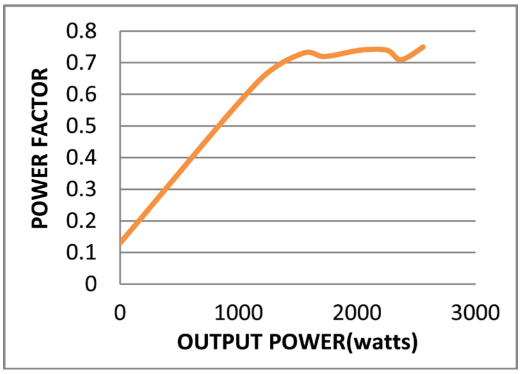

Figure 4. Power factor characteristics.

Table 2. Conventional brake test with excitation 50 V, field current 0.72 A.

Input Voltage (V)	Line Current (A)	Input Power (W)	Output Power (W)	% Efficiency	Power Factor
415	2.5	440	0	0`	0.24
415	3.0	1080	618	83.0	0.50
415	3.5	1520	1047	83.6	0.60
415	4.0	1840	1384	83.0	0.63
415	4.5	2160	1816	84.3	0.66
415	5.0	2400	1954	83.1	0.66
415	5.5	2600	2033	83.4	0.65
415	6.0	2800	2264	78.0	0.64

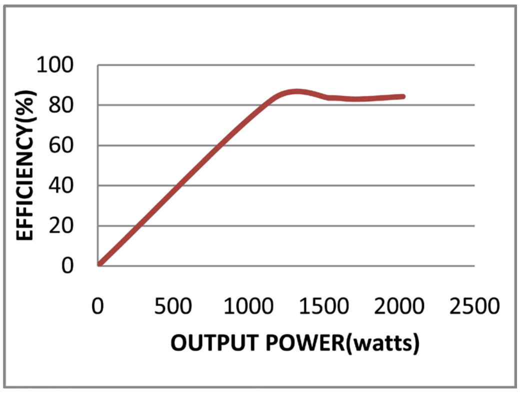

Figure 5. Efficiency characteristics.

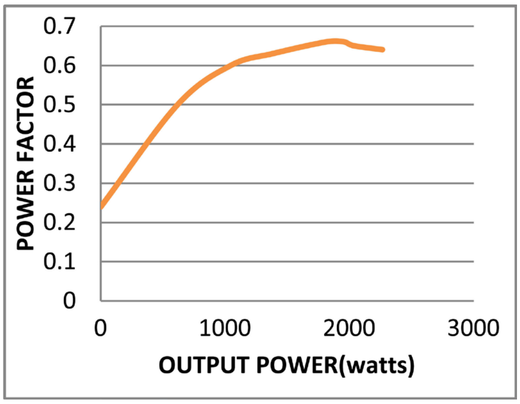

Figure 6. Power factor characteristics.

Table 3 shows the reading observed with rated field excitation with 40 V and field current of 0.62 A. It is observed that the maximum power factor is 0.64 and efficiency is 79.6% for the load current of 5.0 A. The minimum power factor is observed as 0.55 for the load current of 3.5 A, the efficiency of the machine for this load is 55 %. The efficiency and power factor characteristics are shown in **Figure 7** & **Figure 8**. When the excitation is reduced, it is observed that the power factor of the machine decreases.

Table 4 shows the reading observed with rated field excitation with 60 V and field current of 0.85 A. The second winding is connected to a load of 1 A. It is observed that the maximum power factor is 0.95 and efficiency is 85.5% for the load current of 6.0 A. The minimum power factor is observed as 0.71 for the load current of 3.5 A, the efficiency of the machine for this load is 83.1%. The efficiency and power factor characteristics are shown in **Figure 9** & **Figure 10**. When the load is applied on the second set of winding, power factor and efficiency is improved for the same load current.

Table 5 shows the reading observed with field excitation with 50 V and field current of 0.72 A. The second winding is connected to a load of 1 A. It is observed that the maximum power factor is 0.74 and efficiency is 92.3% for the load current of 5.0 A. The minimum power factor is observed as 0.68 for the load current of 3.5 A, the efficiency of the machine for this load is 78.3%. The efficiency and power factor characteristics are shown in **Figure 11** & **Figure 12**.

Table 3. Brake test with excitation 40 V, current 0.62 A.

Input Voltage (V)	Line Current (A)	Input Power (W)	Output Power (W)	% Efficiency	Power Factor
415	2.9	480	0	0	0.23
415	3.5	1400	777	55.0	0.55
415	4.0	1680	1384	82.0	0.58
415	4.5	1960	1520	77.0	0.60
415	5.0	2320	1848	79.6	0.64
415	5.5	2520	1970	78.0	0.63
415	6.0	2760	2094	75.0	0.63

Table 4. Excitation 60 V, field current 0.85 A with 1 A electrical load in second winding.

Line Current (A)	Mechanical Output (W)	Output Voltage (V)	Electrical Output (W)	Total Output (W)	Overall % Efficiency	Overall Power Factor
3.0	0	390	580	580	0	0.46
3.5	777	380	720	1497	83.1	0.71
4.0	1016	375	720	1736	80.0	0.75
4.5	1382	375	720	2102	84.7	0.76
5.0	1663	370	720	2383	82.7	0.80
5.5	1934	365	720	2654	86.1	0.77
6.0	2187	365	720	2907	85.5	0.95

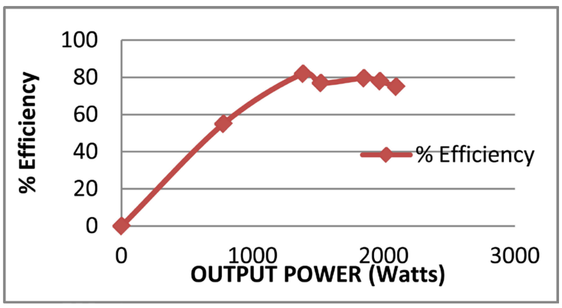

Figure 7. Efficiency characteristics.

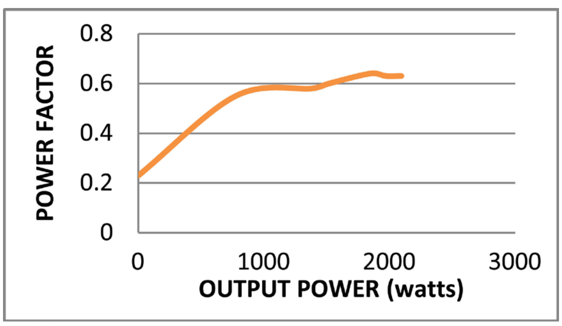

Figure 8. Power factor characteristics.

Table 5. Excitation 50 V, Field current 0.72 A, with 1 A electrical load in second winding.

Line Current (A)	Mechanical Output (W)	Output Voltage (V)	Electrical Output (W)	Total Output (W)	Overall % Efficiency	Overall Power Factor
3.0	0	385	780	780	0	0.46
3.5	647	380	700	1347	78.3	0.68
4.0	1047	375	700	1747	83.3	0.72
4.5	1323	370	720	2043	85.1	0.74
5.0	1775	370	720	2495	92.3	0.74
5.5	1786	365	660	2446	83.7	0.73
6.0	2278	360	640	2918	91.1	0.74

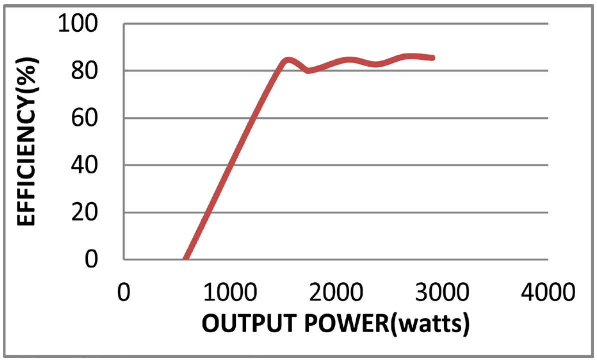

Figure 9. Efficiency characteristics.

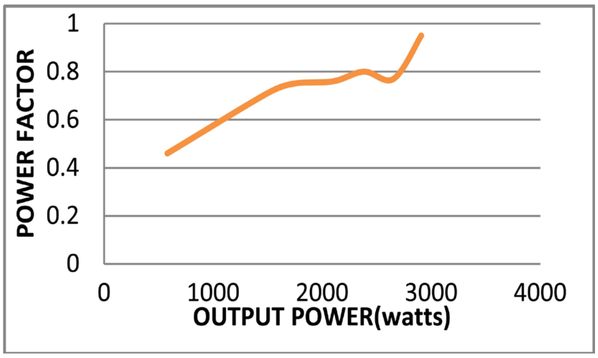

Figure 10. Power factor characteristics.

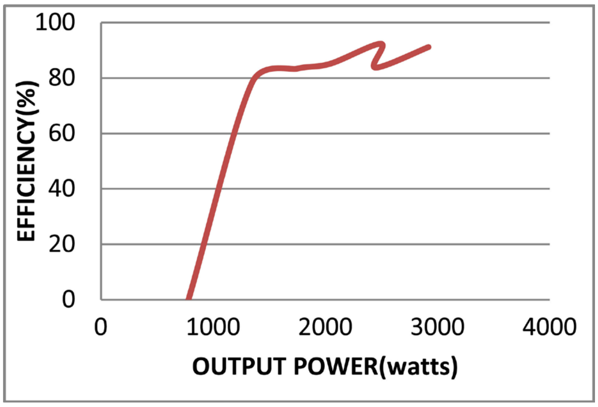

Figure 11. Efficiency characteristics.

Table 6 shows the reading observed with field excitation with 40 V and field current of 0.52 A. The second winding is connected to a load of 1 A. It is observed that the maximum power factor is 0.70 and efficiency is 82.5 % for the load current of 4.8 A. The minimum power factor is observed as 0.66 for the load current of 3.8 A, the efficiency of the machine for this load is 77.6%. The efficiency and power factor characteristics are shown in **Figure 13** & **Figure 14**.

Table 6. Excitation 40V, Field current 0.52A, with 1A electrical load in second winding.

Line Current (A)	Mechanical Output (W)	Output Voltage (V)	Electrical Output (W)	Total Output (W)	Overall % Efficiency	Overall Power Factor
3.3	0	380	720	720	0	0.60
3.8	584	375	720	1304	77.6	0.66
4.3	892	375	720	1612	79.0	0.70
4.8	1294	370	720	2014	82.5	0.70
5.4	1509	365	680	2189	80.4	0.70
6.0	1771	360	680	2451	80.6	0.70

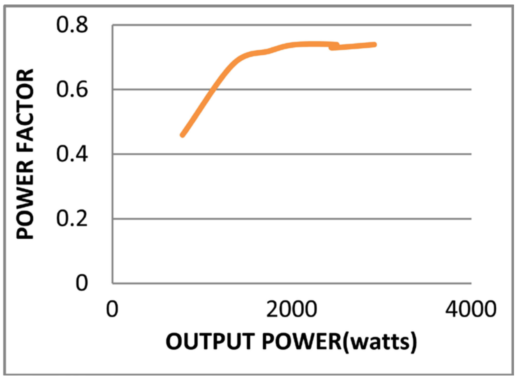

Figure 12. Power factor characteristics.

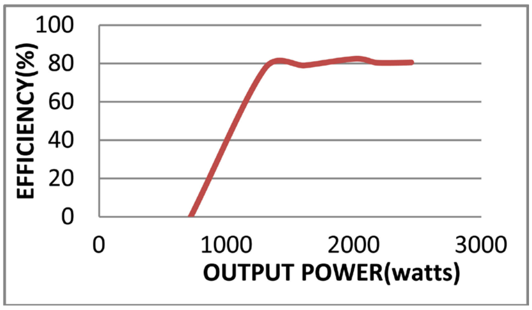

Figure 13. Efficiency characteristics.

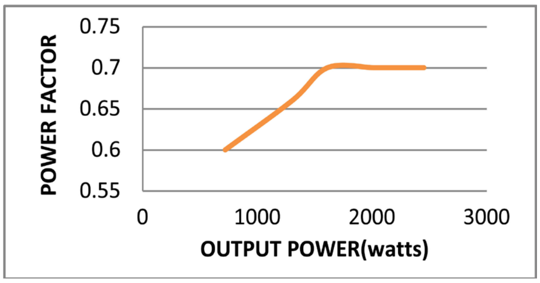

Figure 14. Power factor characteristics.

4. Performance Comparison and Inferences

In conventional synchronous motor, for the given load, when the excitation is decreased, the efficiency and power factor also reduces. The main focus of this paper is to improve the performance of the machine at reduced excitation and minimum load. A series of testing was carried out to study the performance of DWSyM. **Tables 1-3** refer the reading observed during brake test with various excitations. **Figures 3-7** refer the efficiency and power factor characteristics for various excitations. **Tables 4-6** refer the reading observed with both mechanical and electrical load. A 3-phase lamp load and a three-phase loading rheostat are used for loading the second set of winding. **Figures 4-8** refer the efficiency and power factor characteristics for various excitations with electrical load in the second set of winding. The comparison of performance analysis is shown in **Table 7**. For the rated excitation, for the load current of 6 A, efficiency is 78% and power factor 0.78, the same is improved to 85.5% and 0.95 when electrical load is connected in the second of winding. When the excitation is reduced, for the load current of 6 A, the efficiency improves from 78% to 91.1% and power factor improves from 0.64 to 0.74. When the excitation is further reduced for the load current of 3.5A, the efficiency is improved from 55% to 77.6% and power factor from 0.55 to 0.66. In general, dual winding machine provides opportunity to improve its performance for the reduced shaft load while in the conventional machine it is not possible.

4.1. Industrial Application

DWSyM is coupled with centrifugal pump and tested for its performance. Lamp load is connected across the second set of winding. By adjusting the mechanical and electrical loads the machine can be operated simultaneously. The load connected to second set of winding is not depending on separate supply. The designed DWSyM is tested in an industry and the testing set up is shown in **Figure 15**. DWSyM is coupled with a pump, a lamp load is connected in the second winding. Mechanical and electrical outputs are made available in the same machine. Both the loads are adjusted within its thermal limit such that motor is not over loaded.

4.2. Energy Conservation

DWSyM consists of two sets of stator winding. The load connected to the second set of winding is depend on

Table 7. Performance analysis.

Input	Conventional Brake Test Method			With External Load in Second Winding		
	Line Current I_L	% Efficiency	Power Factor	Line Current I_L	% Efficiency	Power Factor
Armature:415 V, 50 Hz, 3-Phase Field: DC 60 V, 0.85 A	5.0	83.1	0.74	5.0	82.7	0.77
	6.0	78.0	0.75	6.0	85.5	0.95
Armature:415 V, 50 Hz, 3-Phase Field: DC 50 V, 0.72 A	4.0	83.0	0.63	4.0	83.0	0.74
	6.0	78.0	0.64	6.0	91.1	0.74
Armature:415 V, 50 Hz, 3-Phase Field: DC 40 V, 0.62 A	3.5	55.0	0.55	3.8	77.6	0.66
	6.0	75.0	0.63	6.0	80.6	0.70

Figure 15. Industrial application.

separate supply. When the machine is not over loaded, by loading both the windings, the machine can be used to rated capacity. For example, if electrical load of 1 A is connected in second winding, power developed in this winding is 700 Watts, if it is operated for 10 hours a day, then the energy conserved is about 210 units per month. When the second winding is loaded, it is also observed that there is slight increase in the input current, however, when compared to the load current of second winding, this is minimum and also accounted.

5. Conclusion

A 3 kW, 3-phase, 4-pole, 1500 rpm, 415 V Double Winding Synchronous Motor was fabricated to verify the performance. The main focus is to improve the performance of synchronous motor during lightly loaded condition; by connecting load on the second winding the overall performance is improved. When operated as conventional motor for the load current of 6 A, the efficiency is 78% and power factor is 0.75, when second winding is connected to a load of 1 A, for the same excitation, the efficiency is improved 85.5% and power factor to 0.95. For the reduced excitation, when operated as conventional motor for a load current of 3.5 A, the efficiency is 55% and power factor is 0.55, when a load of 1 A is connected to the second winding, for the same excitation, the efficiency is improved to 77.6% and power factor to 0.66. This result ensures that there is performance improvement by loading the second set of winding. Another major observation is when the excitation is reduced for the given load torque, the power factor and efficiency of the synchronous motor is reduced; by adjusting load on the second set of winding, the overall performance is improved. Just for a load of 1 A, 210 units is conserved in one month. The Double Winding Synchronous Motor can be used where it is necessary to run continuously like in textile industries and product manufacturing units. The output power from the second winding can be used for charging and supplying lighting loads.

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