http://dx.doi.org/10.5755/j01.eee.21.3.5876

Investigation and Comparison of Three-Phase and Six-Phase Cage Motor Energy Parameters

Juozas Buksnaitis[1]
[1]*Institute of Energetics and Biotechnology Engineering, Aleksandras Stulginskis University, Studentu St. 15-129 A, Akademija, LT – 53361 Kaunas distr., Lithuania*
juozas.buksnaitis@asu.lt

***Abstract*—Factory-produced three-phase 2,2 kW power cage motor with single-layer preformed winding and the same motor after its original winding was replaced with a single-layer preformed six-phase winding was investigated in this work. Electromagnetic properties of the stator windings of the analysed motors were determined after performing the harmonic analysis of rotating magnetomotive forces generated by them and by calculating the electromagnetic efficiency factors according to the results of this analysis. Electromagnetic efficiency factors of both single-layer preformed three-phase and six-phase windings are equal under the same pole count but unequal number of pole and phase slots (k_{ef} = 0,914). All energy parameters of factory-made cage motor and rewound motor were calculated after completing their no-load and load tests and by using the segregated-losses method. It was estimated that under the rated load the phase electric current of rewound cage motor containing a six-phase stator winding decreased by 16,4 %, power input from electric grid decreased by 4,4 %, power losses decreased by 13,5 %, efficiency factor increased by 3,8 %, and power factor increased by 4,7 %, compared to identically loaded factory-made cage motor with respective energy parameters. Research has shown that energy parameters of the six-phase cage motor were noticeably better compared to the three-phase motor, even though the electromagnetic efficiency factors of their windings were equal.**

***Index Terms*—Analysis, induction machine, multi-phase system, single-layer former winding, electromagnetic efficiency factor, energy parameters, performance characteristics.**

I. INTRODUCTION

Recently a lot of scientific works discuss the operation of alternating current electrical machines with six-phase windings. In articles [1]–[4] investigations of six-phase cage motors with asymmetrical and symmetrical stator windings supplied from multi-phase inverters are described. In articles [5]–[8] research of six-phase induction generators and synchronous generators is discussed. However, in these studies there is a lack of more comprehensive information regarding the particular multi-phase machines used in tests and under what conditions tests had been performed using that machinery. Although these sources mention both some certain advantages of motors and generators, their energy parameters are still not being compared with the parameters of three-phase electrical machines.

The aim of the current paper is to describe the accomplished theoretical and experimental investigations of three-phase and six-phase cage motors containing single-layer preformed windings and to compare their electromagnetic and energy-related parameters.

Manuscript received June 9, 2014; accepted December 30, 2014.

II. RESEARCH OBJECT

In this work the 2,2 kW power three-phase cage motor with a single-layer preformed winding (1) and the same motor with its winding replaced with a six-phase alternative of the same type (2) is analysed.

Parameters of three-phase and six-phase single-layer former windings which were used for the purposes of investigation are presented in Table I.

TABLE I. PARAMETERS OF THREE-PHASE AND SIX-PHASE SINGLE-LAYER FORMER WINDINGS.

Winding parameters	Investigated windings	
	1	**2**
Number of phases (m)	3	6
Number of poles ($2p$)	2	2
Number of pole and phase slots (q)	4	2
Number of magnetic circuit slots (Z)	24	24
Pole pitch (τ)	12	12
Winding span (y)	12	10
Slot pitch in electrical degrees (α)	15°	15°

Distribution of the six-phase former winding active coil sides into slots of magnetic circuit is presented in Table II.

TABLE II. DISTRIBUTION OF THE SINGLE-LAYER SIX-PHASE FORMER WINDING ACTIVE COIL SIDES INTO SLOTS OF MAGNETIC CIRCUIT.

Phase change	**U1**	**W2**	**X1**	**Z2**	**V1**	**U2**
Number of coils in a group	2	2	2	2	2	2
Slot No.	1; 2	3; 4	5; 6	7; 8	9; 10	11; 12
Phase change	**Y1**	**X2**	**W1**	**V2**	**Z1**	**Y2**
Slot No.	13; 14	15; 16	17; 18	19; 20	21; 22	23; 24

On the basis of Table II, the electrical diagram layout of the investigated six-phase motor winding and the instantaneous distribution of rotating magnetomotive force generated by this winding were plotted.

The electrical diagram layout of the investigated factory-produced three-phase motor winding and the instantaneous distribution of rotating magnetomotive force generated by this winding are presented in Fig. 2 [9].

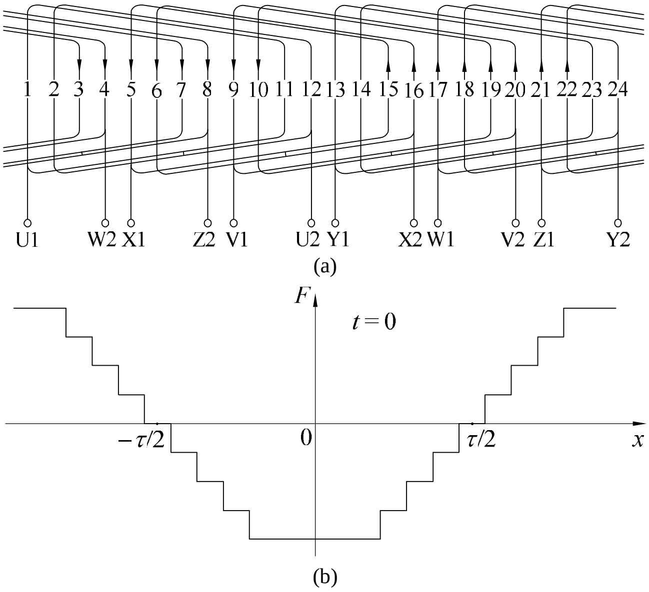

Fig. 1. Electrical diagram layout of single-layer six-phase former winding with q = 2 a); and distribution of rotating magnetomotive forces of this winding at time t = 0 b).

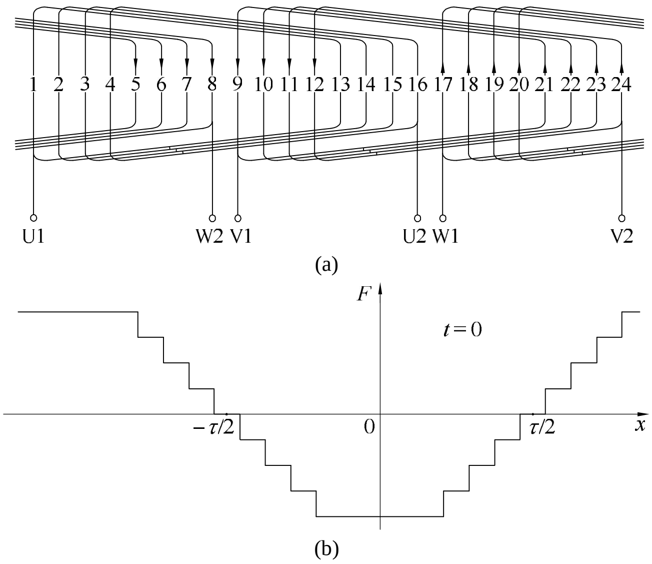

Fig. 2. Electrical diagram layout of single-layer three-phase former winding with q = 4 a); and distribution of rotating magnetomotive forces of this winding at time t = 0 b).

It can be seen from presented tables and figures that the winding span of single-layer pre-formed six-phase winding y, differently from pre-formed three-phase winding span (y = τ = 12), decreased by a magnitude of τ/6 and became equal to 5τ/6 slot pitches (τ = 12; y = 10). As it is known, such optimal winding span reduction significantly decreases the amplitudes of the fifth and seventh harmonics of rotating magnetic fields.

Despite that windings of the investigated motors are identical only in part (windings of the same type, $2p_1 = 2p_2$, $Z_1 = Z_2$), the instantaneous spatial distributions of rotating magnetomotive forces generated by them are identical at any moment of time, as it can be seen from Fig. 1(b) and Fig. 2(b). This means that the electromagnetic parameters of these partially different windings are equal, i.e. the relative magnitudes of their respective ν-th rotating magnetomotive force harmonics and (at the same time) electromagnetic efficiency factors are equal ($k_{ef1} = k_{ef2}$ = 0,914) [9].

III. Evaluation of Parameters of Single-layer Former Six-Phase Winding

After completing the harmonic analysis of rotating magnetomotive force curves it was determined that the conditional amplitude of the fundamental harmonic of rotating magnetomotive force for the analysed motor was F_{m11} = 0,914 [9], and the same amplitude generated by six-phase winding was F_{m12} = 1,829. Because of two-times larger number of phases the amplitude of the fundamental magnetomotive force harmonic created by six-phase winding is doubled, compared to the same amplitude of three-phase winding under identical electrical supply conditions for both windings. Under the same magnitude of magnetomotive force, the magnetic circuits of six-phase cage motor stator and rotor would be rather oversaturated and its energy parameters would be poor. In order to maintain the magnetic circuit saturation similar to three-phase motor for which it was estimated during its design, the six-phase motor phase supply voltage was decreased almost twice, i.e. down to U_{f2} = 130 V.

According to the cage motor design manuals and assuming that six-phase cage motor rated power would remain the same as for three-phase motor ($P_{n1} = P_{n2}$ = 2,2 kW), its air gap magnetic flux density was selected: B_δ = 0,65 T. According to this density the rotating magnetic flux amplitude value was determined

$$\Phi_\delta = \alpha_\delta \times B_\delta \times \tau \times l = 0,637 \times 0,65 \times 0,1147 \times 0,098 = \\ = 4,654 \times 10^{-3} \, [Wb], \qquad (1)$$

where α_δ – pole factor; τ – pole pitch, m; l – length of stator magnetic circuit, m.

Magnetic flux density in stator teeth

$$B_z = B_\delta \times \left(Q_\delta / Q_z\right) = 0,65 \times \left(0,01124 / 0,00403\right) = \\ = 1,81 \, [T], \qquad (2)$$

where Q_δ – pole pitch area, m^2; Q_z – teeth cross-section area over a pole pitch, m^2.

Magnetic flux density in stator yoke

$$B_j = \Phi_\delta / \left(2Q_j\right) = 4,654 \times 10^{-3} / \left(2 \cdot 0,001415\right) = \\ = 1,645 \, [T], \qquad (3)$$

where Q_j – stator yoke cross-section area, m^2.

Obtained six-phase motor magnetic flux densities in stator teeth and yoke do not exceed the permitted values.

Distribution factor of former six-phase winding

$$k_p = sin\left(0,5 \times \alpha \times q\right) / \left(q \times sin\left(0,5 \times \alpha\right)\right) = \\ = sin\left(0,5 \times 15^\circ \times 2\right) / \left(2 \times sin\left(0,5 \times 15^\circ\right)\right) = 0,991. \qquad (4)$$

Former six-phase winding pitch factor

$$k_y = sin\left(0,5y\pi/\tau\right) = sin\left(0,5\times10\times180^\circ/12\right) = 0,966. \quad (5)$$

Former six-phase winding factor

$$k_w = k_p \times k_y = 0,991\times0,966 = 0,957. \quad (6)$$

Number of turns in a single phase of six-phase stator winding

$$W' = k_U \times U_{f2} / \left(4,44\times f \times k_w \times \Phi'\right) =$$
$$= 0,97\times130/\left(4,44\times50\times0,957\times4,654\times10^{-3}\right) = 128, \quad (7)$$

where k_U – factor estimating the voltage drop in stator windings.

Number of effective conductors in stator slot

$$N = 12\times W'/Z = 12\times128/24 = 64. \quad (8)$$

Preliminary cross-section area of elementary conductor

$$q' = Q_s \times k_{Cu} / N = 85,8\times0,42/64 = 0,563\left[mm^2\right], \quad (9)$$

where Q_s – stator slot area, mm^2; k_{Cu} – slot copper fill factor.

According to the estimated preliminary conductor cross-section area, the standard conductor dimensions for six-phase winding are determined from catalog: q = 0,567 mm^2; d = 0,85 mm; d_{is} = 0,915 mm.

Slot fill factor for conductors was calculated as

$$k_{fi} = d_{is}^2 \times N / Q_s' = 0,915^2\times64/75,5 = 0,71, \quad (10)$$

where Q_s' – slot area without isolation.

Determined fill factor indicates that parameters of pre-formed six-phase winding were estimated correctly and it could be laid into the stator slots without any problems.

IV. CAGE MOTOR RESEARCH RESULTS

Initially the no-load test of three-phase cage motor with a single-layer former winding has been carried out. During this test, motor supply voltage U_1 was varied within certain limits using induction voltage regulator. Results of this test are given in Table III.

TABLE III. RESULTS OF THREE-PHASE MOTOR NO-LOAD TEST.

No.	U_1, V	$U_1^2 \cdot 10^4$, V^2	P_{Of}, W	$P_{1O}=3\cdot P_{Of}$, W
1	80	0,64	106	318
2	100	1,0	110	330
3	120	1,44	118	354
4	140	1,96	130	390
5	160	2,56	140	420
6	180	3,24	149	447
7	200	4,0	165	495
8	210	4,41	180	540
9	220	4,84	205	615

Here P_{10} – consumed power (constant power losses).

Based on the test results, characteristic of function P_{10} = f$\left(U_1^2\right)$ was plotted (Fig. 3).

From this characteristic we graphically determined the no-load mode (constant) power losses (mechanical P_f and magnetic P_m power losses) for the analysed motors. The following losses for the three-phase cage motor under its supply voltage U_{f1} = 230 V were obtained: P_{f1} = 280 W, P_{m1} = 305 W. Graphically estimated constant losses of rewound six-phase motor with supply voltage U_{f2} = 130 V were as follows: P_{f2} = 280 W, P_{m2} = 100 W.

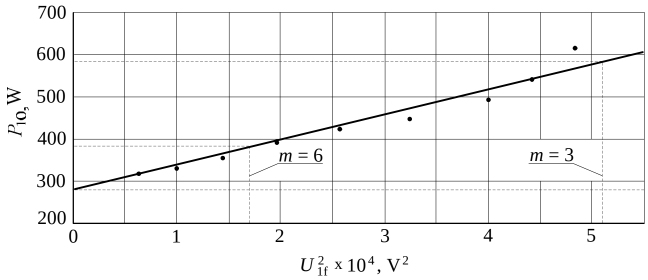

Fig. 3. Characteristic of three-phase cage motor function P_{10} = f$\left(U_1^2\right)$.

Then we completed a test of the three-phase cage motor with a single-layer former winding, by varying its load. During the test this motor was supplied from industrial three-phase network and was loaded using a direct current generator. Based on test results (I_1, P_1, n) other energy-related parameters of the analysed motor were calculated by applying the segregated-losses method (Table IV).

TABLE IV. EXPERIMENTAL AND CALCULATION RESULTS FOR THREE-PHASE CAGE MOTOR WITH SINGLE-LAYER FORMER WINDING.

No.	1	2	3	4	5	6
I_1, A	5,3	4,75	4,25	3,85	3,65	3,6
P_1, W	3020	2540	2050	1590	1140	735
n, min^{-1}	2868	2888	2910	2936	2958	2980
ω, s^{-1}	300,3	302,4	304,7	307,4	309,7	312,0
s	0,044	0,037	0,030	0,021	0,014	0,007
P_{e1}, W	282,3	226,8	181,5	149,0	133,9	130,2
P_{em}, W	2433	2008	1564	1136	701	300
P_{e2}, W	107,1	74,9	46,9	24,2	9,8	2,0
P_{mech}, W	2326	1933	1517	1112	691	298
M_{em}, Nm	7,75	6,39	4,98	3,62	2,23	0,955
P_p, W	15,8	12,7	10,2	8,3	7,5	7,3
ΣP, W	990	899	824	766	736	725
P_2, W	2030	1641	1226	824	404	10
η	0,672	0,646	0,598	0,518	0,354	0,014
cos φ	0,840	0,789	0,711	0,609	0,461	0,301

Here I_1 – phase current; P_1 – power input from network; n – rotational speed; ω – angular rotational velocity; s – rotor slip; P_{e1}, P_{e2} – electric power losses; P_{em} – electromagnetic power; P_{mech} – mechanic power; M_{em} – electromagnetic momentum; P_a – supplementary power losses; ΣP – cumulative power losses; P_2 – net power; η – efficiency factor; cos φ – power factor.

Three-phase stator winding of the examined cage motor (Fig. 2) with the parameters as calculated in the Section III was replaced with a six-phase winding (Fig. 1). When varying the load of the rewound six-phase motor, experimental tests were conducted. During the tests, the analysed motor was supplied from a step-down transformer (U_{2f} = 130 V) containing secondary six-phase winding, and was loaded using the same generator as in case of the previous three-phase motor. Based on test results (I_1, P_1, n), other energy-related parameters of the analysed six-phase motor were calculated using the segregated-losses method (Table V).

TABLE V. EXPERIMENTAL AND CALCULATION RESULTS FOR SIX-PHASE CAGE MOTOR WITH SINGLE-LAYER FORMER WINDING.

No.	1	2	3	4	5	6	7
I_1, A	4,43	3,81	3,40	3,05	2,62	2,25	2,10
P_1, W	2985	2485	2140	1823	1373	873	450
n, min^{-1}	2811	2823	2845	2870	2911	2948	2979
ω, s^{-1}	294	296	298	300	305	309	312
s·10^{-2}	6,3	5,9	5,17	4,33	2,97	1,73	0,7
P_{e1}, W	318	235	187	151	111	82,0	71,4
P_{em}, W	2567	2150	1853	1572	1162	691	279
P_{e2}, W	162	127	95,8	68,1	34,5	12,0	2,0
P_{mec}, W	2405	2023	1757	1504	1128	679	277
M_{em}, Nm	8,17	6,84	5,90	5,00	3,70	2,20	0,89
P_p, W	18,2	13,4	10,7	8,6	6,4	4,7	4,1
ΣP, W	878	755	674	607	532	479	458
P_2, W	2107	1730	1466	1216	841	394	–8,0
η·10^{-2}	70,6	69,6	68,5	66,7	61,3	45,1	–1,8
cos φ	0,88	0,85	0,82	0,78	0,68	0,50	0,28

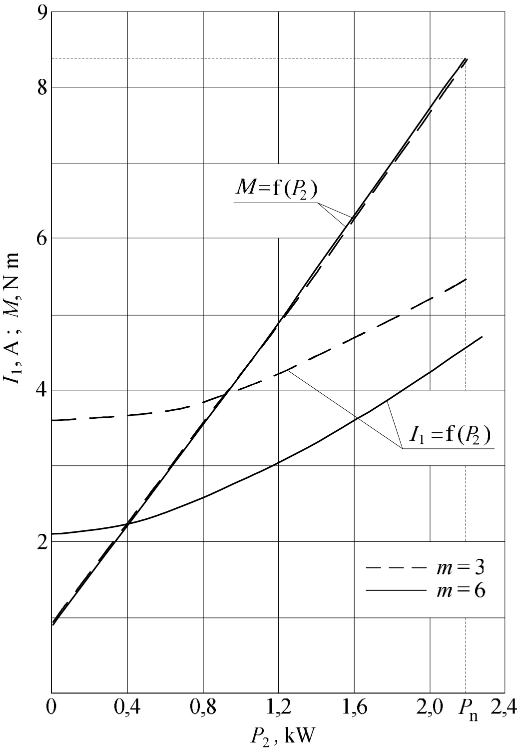

Fig. 4. Characteristics of the investigated cage motors: functions I_1 = f(P_2) and M = f(P_2).

Three-phase stator winding of the examined cage motor (Fig. 2) with the parameters as calculated in the Section III was replaced with a six-phase winding (Fig. 1). When varying the load of the rewound six-phase motor, experimental tests were conducted. During the tests, the analysed motor was supplied from a step-down transformer (U_{2f} = 130 V) containing secondary six-phase winding, and was loaded using the same generator as in case of the previous three-phase motor. Based on test results (I_1, P_1, n), other energy-related parameters of the analysed six-phase motor were calculated using the segregated-losses method (Table V).

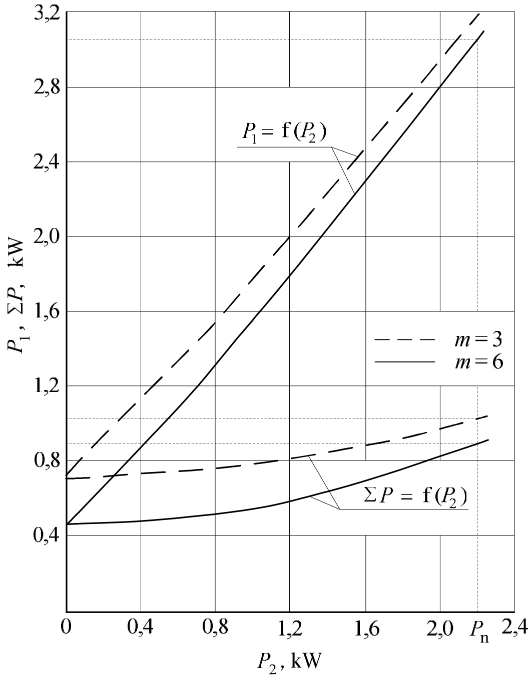

Fig. 5. Characteristics of the investigated cage motors: functions P_1 = f(P_2) and ΣP = f(P_2).

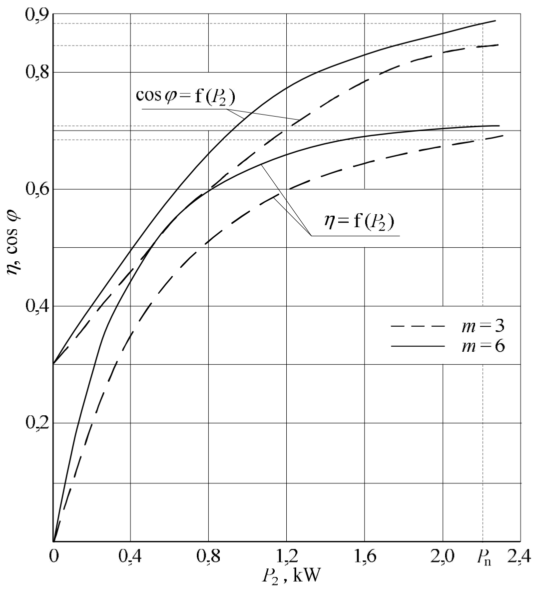

Fig. 6. Characteristics of the investigated cage motors: functions η = f(P_2) and cos φ = f(P_2).

Based on the obtained results, performance characteristics of the investigated motors were plotted.

In diagrams presented in Fig. 4–Fig. 6 the change of three-phase and six-phase induction motor energy parameters under different loads and also differences between those parameters can be clearly seen. Based on these figures some conclusions were suggested.

V. CONCLUSIONS

Single-layer former six-phase winding span, differently from the span of the same type three-phase winding which is equal to the pole pitch, is reduced by one sixth of the pole pitch and thus becomes optimal.

After replacing the three-phase winding in the stator magnetic circuit with the six-phase equivalent containing the same number of poles, the relative magnitudes of rotating magnetic field of the higher harmonics generated by it remain the same as for three-phase winding.

To avoid the unacceptable over saturation of six-phase motor stator and rotor magnetic circuits resulting from the increased number of phases, it has to be supplied using significantly stepped-down industrial network voltage ($U \approx 130$ V).

For the rewound six-phase cage motor loaded by the rated load, the phase current decreased by 16,4 %, power required from the network decreased by 4,4 %, power losses decreased by 13,5 %, power factor increased by 4,7 %, efficiency factor increased by 3,8 %, and electromagnetic momentum remained almost unchanged, compared to the same parameters of three-phase motor.

Even though the six-phase motor with a single-layer former winding was not designed especially for this purpose, it can be seen from the results of this investigation that all its energy parameters are noticeably better compared to the same parameters of the three-phase motor.

REFERENCES

[1] G. K. Singh, V. Pant, Y. P. Singh, "Stability analysis of a multi-phase (six-phase) induction machine", *Computers and Electrical Engineering*, no. 29, pp. 727–756, 2003. [Online]. Available: http://dx.doi.org/10.1016/S0045-7906(03)00003-X

[2] S. N. Vukosavic, M. Jones, E. Levi, J. Varga, "Rotor fluxoriented control of a symmetrical six-phase induction machine", *Electric Power Systems Research*, no. 75, pp. 142–152, 2005. [Online]. Available: http://dx.doi.org/10.1016/j.epsr.2005.02.006

[3] R. Kianinezhad, B. Nahid, L. Baghi, F. Betin, G. A. Capolino, "Modeling and control of six-phase symmetrical induction machine under fault condition due to open phases", *IEEE Trans Ind Appl*, vol. 55, no. 5, pp. 1966–1977, 2008. http://dx.doi.org/10.1109/tie.2008.918479

[4] V. Talaeizadeh, R. Kianinezhad, S. G. Seyfossadat, H. A. Shayanfar, "Direct torque control of six-phase induction motors using three-phase matrix converter", *Conversion and Management*, no. 51, pp. 2482–2491, 2010.

[5] G. K. Singh, A. Senthil Kumar, R. P. Saini, "Performance evaluation of series compensated self-excited six-phase induction generator for stand-alone renewable energy generation", *Energy*, no. 35, pp. 288–297, 2010. [Online]. Available: http://dx.doi.org/10.1016/j.energy.2009.09.021

[6] G. K. Singh, "A six-phase synchronous generator for stand-alone renewable energy generation: Experimental analysis", *Energy*, no. 36, pp. 1768–1775, 2011. [Online]. Available: http://dx.doi.org/10.1016/j.energy.2010.12.052

[7] G. K. Singh, D. Singh, *Transient analysis of isolated six-phase synchronous generator*. Indian Institute of technology, Roorkeem India, pp. 73–80, 2012.

[8] A. Senthil Kumar, J. L. Munda, G. K. Singh, "Steady-state and dynamic load performance of six-phase self-exited induction generator", *Int. Conf. on Integrated Waste Management and Green Energy Engineering*, Johannesburg, South Africa, 2013, pp. 292–296.

[9] J. Buksnaitis, *Electromagnetic efficiency of windings three-phase alternating current electric machines: monograph*. Aleksandras Stulginskis University, Kaunas: Technology, Lithuania, 2007, p. 196.