Maximum efficiency control of six- and three-phase two-motor drives

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Abstract: In this study, a method for loss minimisation of six- and three-phase two-motor drive systems is presented. In two-motor drive systems (or multiphase multi-motor drive systems), currents of one motor pass through the other motor(s), which lead to increment of copper loss. In the proposed method for loss minimisation of six- and three-phase two-motor drive systems, extra copper loss of the six-phase motor, caused by reference currents of three-phase motor, is considered in loss-minimisation equations of three-phase motor; therefore the total controllable loss (including copper and iron losses) of whole system will be minimised in a unified form. In this paper, amount of efficiency improvement of proposed method for a system of two six- and three-phase motors in different speeds and load torques are compared with a conventional method of nominal flux. Also experimental results verify performance of the proposed method.

Nomenclature

V_d, V_q	d- and q-axis components of stator voltage
i_d, i_q	d- and q-axis components of current
i_{cd}, i_{cq}	d- and q-axis iron loss components of current
L_m	magnetising inductance
L_{ls}, L_{lr}	stator and rotor leakage inductances
R_s	stator resistance
R_c	iron loss resistance
P_{cu-s}, P_{cu-r}	stator and rotor copper loss
P_{Fe}	iron loss
ω_r	rotor mechanical speed
ω	electrical frequency
P	pole pairs
T_e	electromagnetic torque

1 Introduction

In many applications, such as electric vehicle/hybrid vehicle (EV/HV), railway traction, more electric aircraft and electric ship propulsion, multiphase machines are utilised due to advantages including reduction of the inverter per-phase rating, less noise pollution, higher efficiency, reduced torque pulsations, greater tolerance to open-circuit faults and so on [1–4]. In addition to these benefits, two or more multiphase machines can be controlled by increasing phase number to at least five or more from a single current-controlled voltage source inverter (VSI) [5]. This advantage extends the applicability of multiphase multi-motor systems to a variety of applications which require more than one motor such as locomotive traction, heating, ventilation and air-conditioning (HVAC) and so on [6].

Main idea and connection diagram of multiphase multi-motor systems are presented in [7, 8] for odd and even phase numbers, respectively. Based on this idea, two components of current are required for vector control of each multiphase motor; therefore the remaining degrees of freedom can be used for controlling the other motors which are to be connected in series with the first motor [5]. Accordingly, motors should be connected with an appropriate phase transposition from one motor to the other.

In [9], steady-state modelling of five-phase and six-phase two-motor drives is presented. It is shown in this paper that the specific winding connections results in less dc-link voltage requirement in comparison to the situation that the windings have been connected directly in series. Also, in [6, 10], dynamic modelling of two-motor drives is discussed.

In [11], a method for voltage control of two six- and three-phase motor drives is presented. It is shown that how to achieve

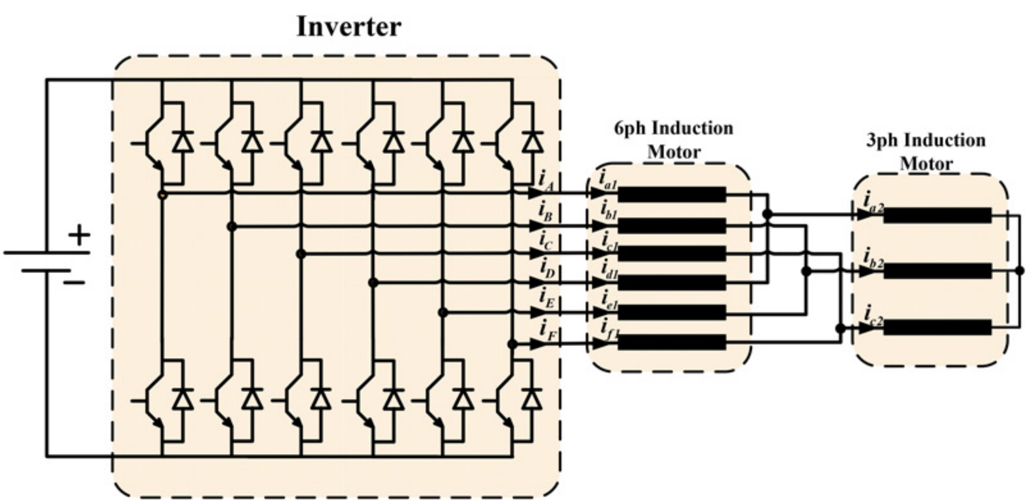

Fig. 1 *Connection diagram of two six- and three-phase motor drives*

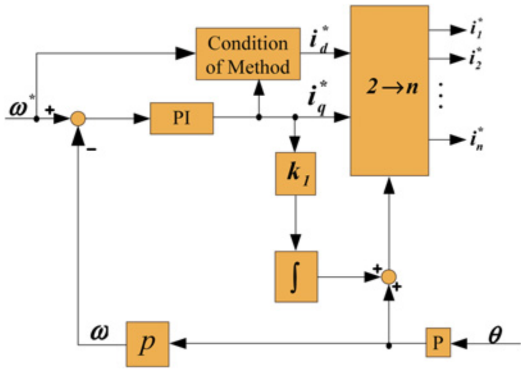

Fig. 2 *Block diagram of indirect vector control of n-phase induction motor*

independent feedforward voltage control and to evaluate the switched voltage profile in the motors' windings and their behaviour.

In multiphase multi-motor systems, utilising different types of motors (including induction, synchronous reluctance, permanent magnet synchronous motors etc.) is possible. In [12], two induction and synchronous reluctance motors, and in [13], two induction and permanent magnet synchronous motors are connected in series in two six- and three-phase motor drive system. It is experimentally verified in these references that in addition to independent control of the two motors, there is no negative impact on the transient performance of both motors.

Increased copper loss in multiphase multi-motor systems leads to decrement of efficiency to some extent. As stated in [12],

Table 1 Six-phase motor parameters

R_s, Ω	0.880
R_r, Ω	0.335
R_c, Ω	Fig. 3*a*
L_m, H	0.0795
L_{ls}, H	0.00245
L_{lr}, H	0.00245
friction and windage torque, N m	Fig. 3*b*
number of pole pairs	2
rated speed, rpm	1400
rated power, kW	2.2

Table 2 Three-phase motor parameters

R_s, Ω	3.0
R_r, Ω	2.66
R_c, Ω	Fig. 3*c*
L_m, H	0.179
$L_{ls,}$ H	0.0148
L_{lr}, H	0.0148
friction and windage torque, N.m	Fig. 3*d*
number of pole pairs	4
rated speed, rpm	690
rated power, kW	2.2

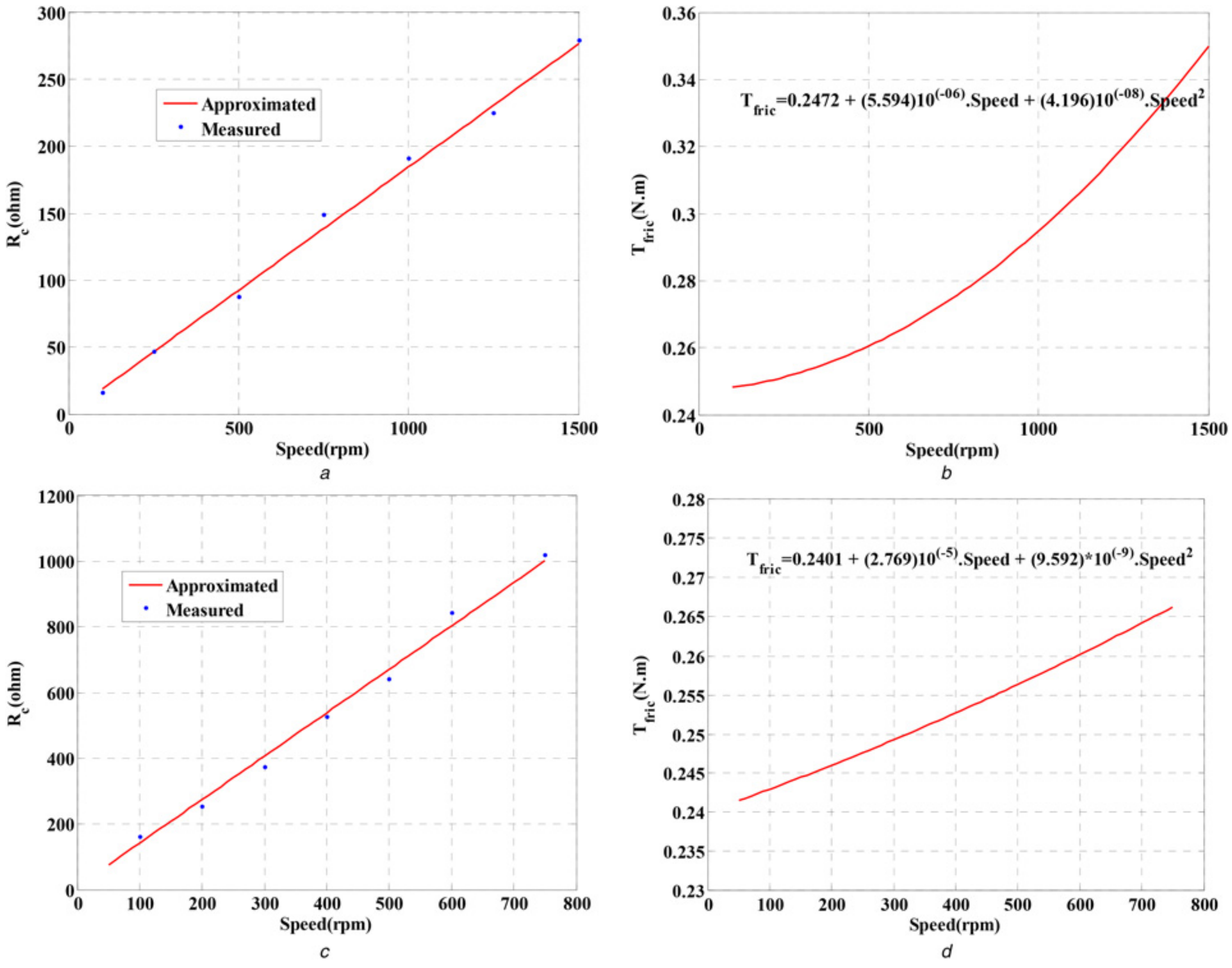

Fig. 3 *Measured iron loss resistance (as a function of speed in no-load) and friction and windage torque of six-phase and three-phase motors*
a Iron loss resistance of six-phase motor
b Friction and windage torque of six-phase motor
c Iron loss resistance of three-phase motor
d Friction and windage torque of three-phase motor

one of the best applications of these systems is wider application. However, efficiency improvement of these systems can have great importance.

There are different methods for loss minimisation of a single induction motor. Generally, these methods can be divided into three main groups of search-based, model-based and hybrid methods.

In search-based control methods, the control variable would be perturbed by a specified process in order to minimise input power. In [14], output voltage in a scalar method would be changed in such a way that stator current will be minimised. In general, main advantage of search-based methods is motor parameter independency and its simplicity in implementation. However, the drawbacks of these methods are low dynamic response and oscillating around operating point. These drawbacks limit utilisation of search-based methods in some applications which model-based methods should be utilised in.

In model-based methods [15–21], loss minimisation is based on motor model. In [15], the loss-minimisation condition is obtained by differentiating controllable loss equation (sum of copper and iron losses) with respect to *d*-axis current and equating the derivative to zero. In [16], an analysis is done on loss minimisation of induction motors. Based on experimental results of [16] on two different motors with power ratings of 22 and 90 kW, it is not critical if the converter losses are neglected in the control system for loss minimisation. Therefore, from the view point of efficiency, there is not considerable difference between the case of 'considering converter loss' and the case of 'not considering converter loss', because their operating points are close together. Generally, the main advantage of model-based methods is fast dynamic response to reach optimum operating point.

In hybrid methods [22, 23], a combination of model-based and search-based methods is utilised. In [23], a ripple correlation

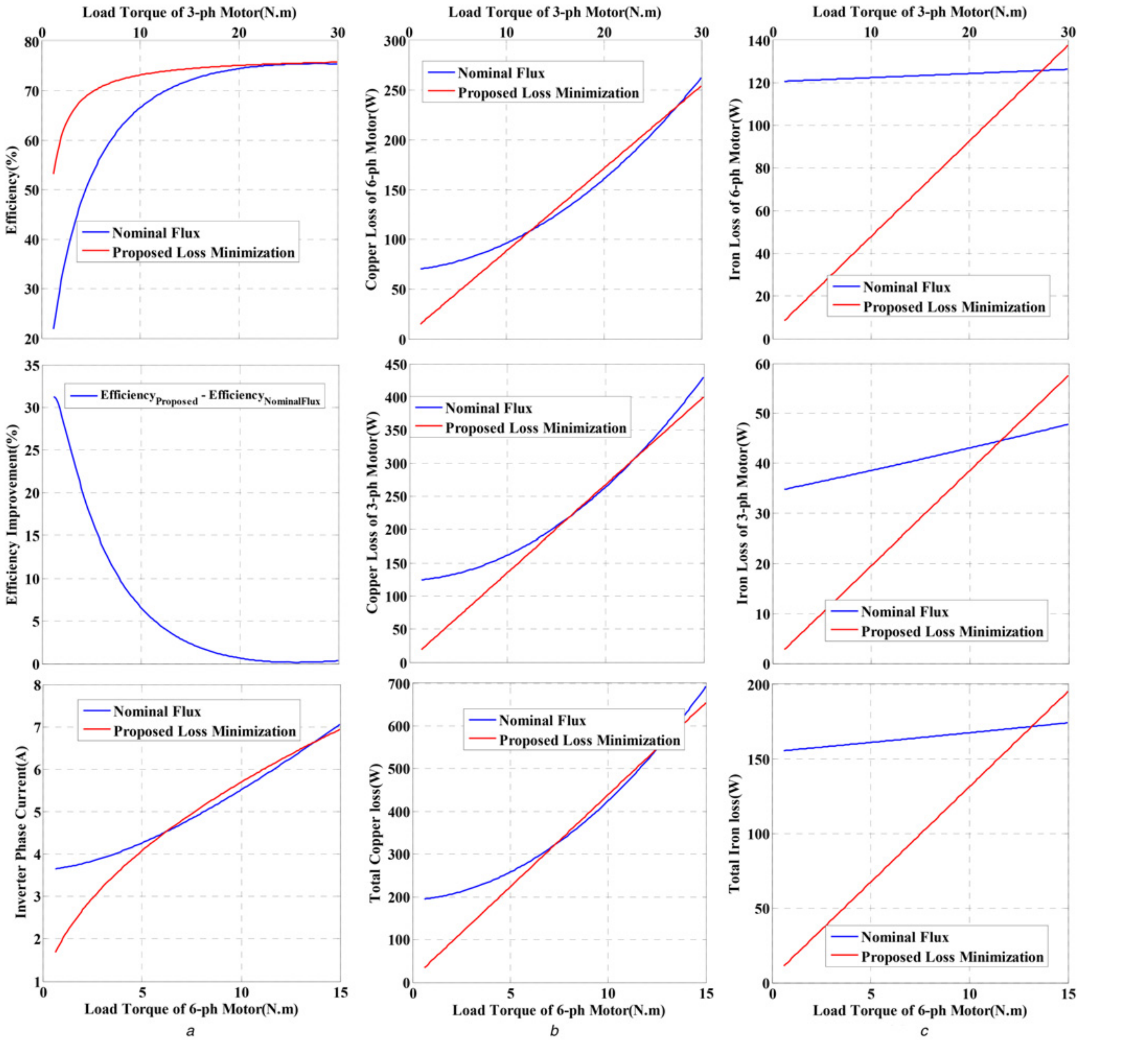

Fig. 4 *Comparison of proposed method and nominal flux method in different load torques and constant speeds – speed of three-phase motor is 200 rpm and speed of six-phase motor is 1400rpm*
a Total efficiency, efficiency improvement of proposed method in comparison with nominal flux method and inverter phase current
b Copper loss of six-phase motor, copper loss of three-phase motor and total copper loss
c Iron loss of six-phase motor, iron loss of three-phase motor and total iron loss

control (RCC) approach is utilised as a hybrid method. In this method, extremum-seeking control is done by using inherent ripple in power electronics. However, RCC requires a rotor flux estimate, which is dependent on motor parameters.

In this paper, at first, two six- and three-phase motor series-connected drive systems are discussed. In Section 3, loss-minimisation control of a single induction motor is investigated. Later, in Section 4, proposed loss-minimisation control method of two six- and three-phase motor drives is presented. The effect of using proposed method in comparison with nominal flux control method is discussed in Section 5. Finally, experimental results are presented in order to verify the performance of the proposed methods.

2 Two six- and three-phase motor series-connected drives

In two six- and three-phase motor series-connected drive systems, both motors can be controlled independently via single inverter. Connection diagram of this system has been established in [8] which is shown in Fig. 1. Also block diagram of the control system is shown in Fig. 2. This block diagram is utilised for each of the two motors in order to obtain current references of each motor. Then phase current references of the motors are added with each other based on (1) to obtain phase current references of the inverter. Finally, inverter current references will be applied to the motor via hysteresis current controller

$$\begin{aligned} i_A^* &= i_{a1}^* + \frac{i_{a2}^*}{2}\ ; \quad i_D^* = i_{d1}^* + \frac{i_{a2}^*}{2} \\ i_B^* &= i_{b1}^* + \frac{i_{b2}^*}{2}\ ; \quad i_E^* = i_{e1}^* + \frac{i_{b2}^*}{2} \\ i_C^* &= i_{c1}^* + \frac{i_{c2}^*}{2}\ ; \quad i_F^* = i_{f1}^* + \frac{i_{c2}^*}{2} \end{aligned} \tag{1}$$

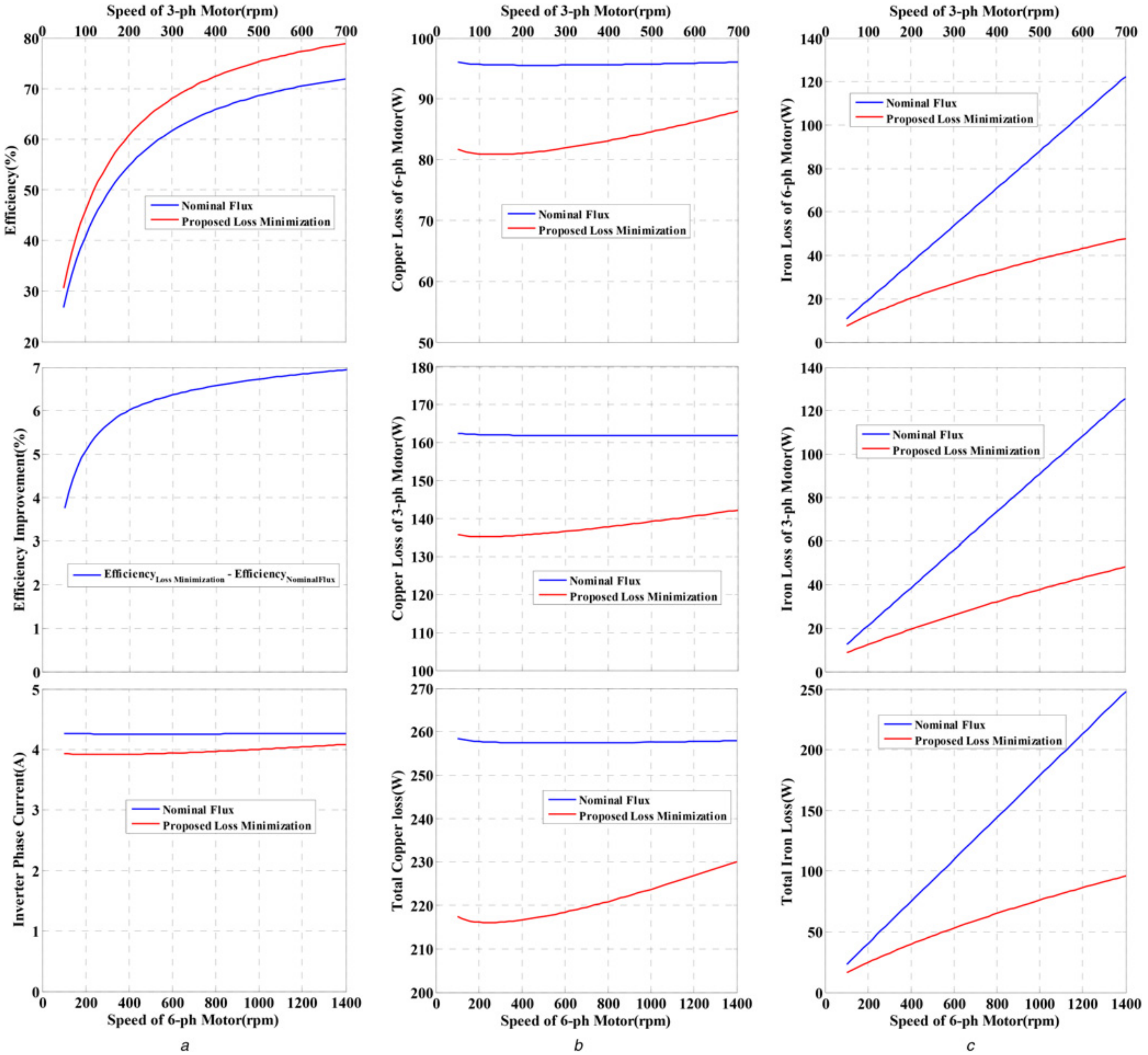

Fig. 5 *Comparison of proposed method and nominal flux method in different speeds and constant loads – load torque of both of three-phase and of six-phase motors is 10 N m*
a Total efficiency, efficiency improvement of proposed method in comparison with nominal flux method and inverter phase current
b Copper loss of six-phase motor, copper loss of three-phase motor and total copper loss
c Iron loss of six-phase motor, iron loss of three-phase motor and total iron loss

3 Maximum efficiency control of induction motors

In model-based maximum efficiency control method of induction motors, at first, total controllable loss, including copper loss and iron loss, should be differentiated with respect to d-axis current and equating the derivative to zero. Controllable loss components are as follows:

$$\begin{aligned} P_{\text{cu}-\text{s}} &= (R_\text{s})\cdot(i_d^2+i_q^2) \\ P_{\text{cu}-\text{r}} &= (R_\text{r})\cdot\left(i_q-\frac{\omega_\text{s}L_\text{m}}{R_\text{fe}}i_d\right)^2 \\ &= (R_\text{r})\cdot\left(i_q^2+\left(\frac{\omega_\text{s}L_\text{m}}{R_\text{fe}}\right)^2 i_d^2-2\frac{\omega_\text{s}L_\text{m}}{R_\text{fe}}i_d i_q\right) \\ P_\text{fe} &= \frac{(\omega_\text{s}L_\text{m})^2}{R_\text{fe}}.i_d^2 \end{aligned} \tag{2}$$

Condition of maximum efficiency control of induction motors, which is concluded by differentiating sum of controllable losses with respect to d-axis current and equating the derivative to zero [15]

$$i_d=\sqrt{\frac{(R_\text{s}+R_\text{r})}{\left[((\omega_\text{s}L_\text{m})^2/R_\text{fe})+R_\text{s}+((\omega_\text{s}L_\text{m}/R_\text{fe}))^2R_\text{r}\right]}}\cdot i_q \tag{3}$$

4 Maximum efficiency control of two six- and three-phase motor drives

In two six- and three-phase motor systems, each phase current of three-phase motor comes from two phases of six-phase motor, while currents of six-phase motor do not pass from three-phase motor windings. Total copper loss of each motor is as follows:

$$\begin{aligned} P_{\text{cu}-6\varphi} &= \left(6\cdot R_{\text{s}-6\varphi}\cdot(i_{6\varphi})^2+6\cdot R_{\text{s}-6\varphi}\cdot\left(\frac{i_{3\varphi}}{2}\right)^2\right) \\ &= \left(6\cdot R_{\text{s}-6\varphi}\cdot\left(i_{6\varphi}^2\right)+3\cdot\left(\frac{R_{\text{s}-6\varphi}}{2}\right)\cdot(i_{3\varphi})^2\right) \\ P_{\text{cu}-3\varphi} &= 3\cdot\left(R_{\text{s}-3\varphi}\right)\cdot(i_{3\varphi})^2 \end{aligned} \tag{4}$$

Therefore, extra copper loss produced in six-phase motor, caused by reference currents of three phase motor, should be considered in maximum efficiency control of three phase motor. Therefore, in maximum efficiency control of these two motors, the following equations should be used in maximum efficiency control of each motor:

$$\begin{aligned} P_{\text{cu}-6\varphi-\text{used in control system}} &= 6\cdot R_{\text{s}-6\varphi}\cdot(i_{6\varphi})^2 \\ P_{\text{cu}-3\varphi-\text{used in control system}} &= 3\cdot\left(R_{\text{s}-3\varphi}\right)\cdot(i_{3\varphi})^2+6\cdot R_{\text{s}-6\varphi}\cdot\left(\frac{i_{3\varphi}}{2}\right)^2 \end{aligned} \tag{5}$$

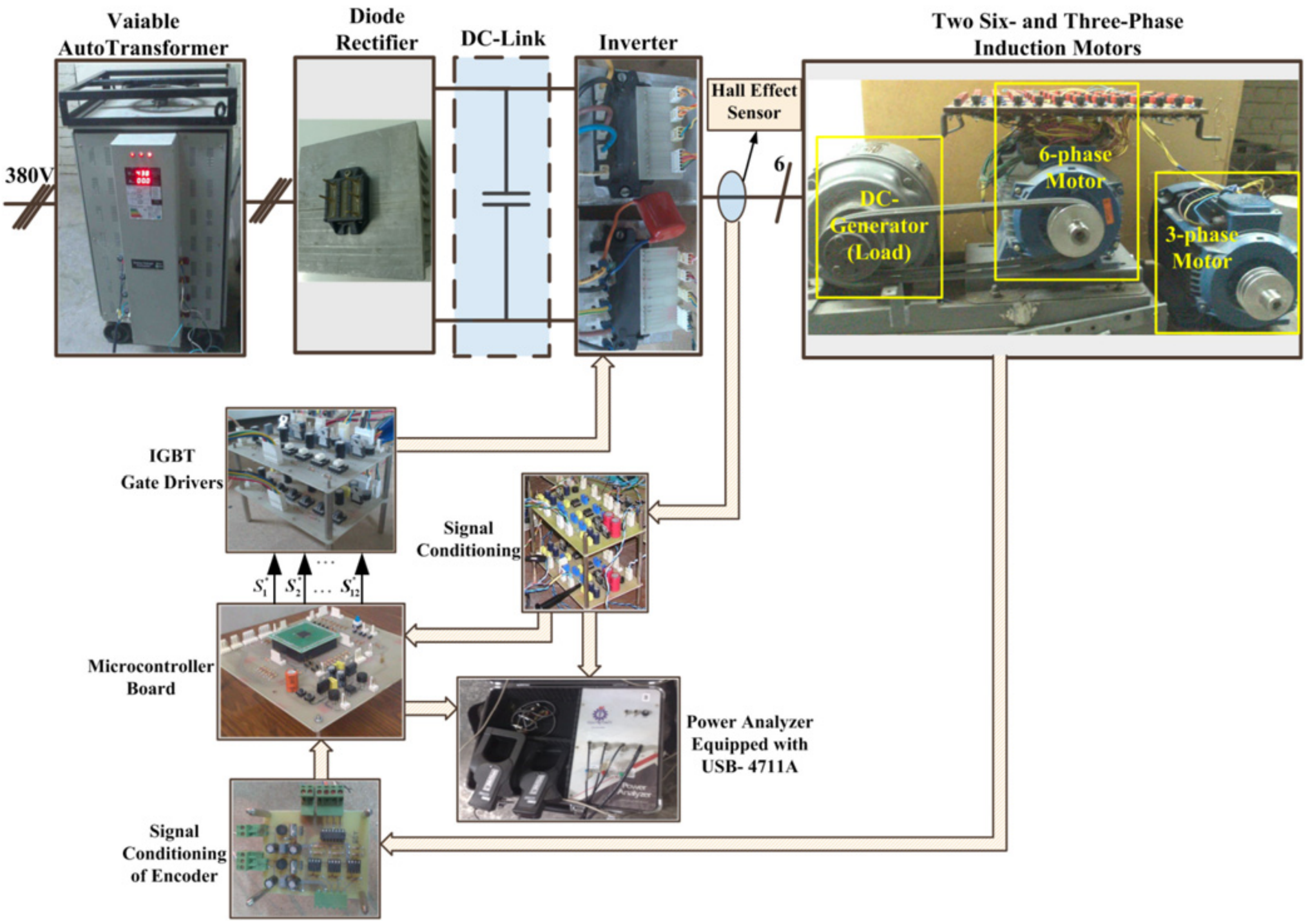

Fig. 6 *Experimental setup*

In fact, the term of $\left(6 \cdot R_{s-6\varphi} \cdot (i_{3\varphi}/2)^2\right) = \left(3 \cdot (R_{s-6\varphi}/2) \cdot (i_{3\varphi}^2)\right)$ is a component of copper loss of six-phase motor, but this term is controlled by reference currents of three-phase motor. Therefore, in maximum efficiency control of three-phase motor, this term should be added to copper loss of three-phase motor. In better words, stator resistance of three-phase motor should be considered equal to $\left(R_{s-3\varphi} + (R_{s-6\varphi}/2)\right)$ in maximum efficiency control of three-phase motor, and also stator resistance of six-phase motor should be considered equal to $R_{s-6\varphi}$ in maximum efficiency control of six-phase motor.

5 Comparison of proposed maximum efficiency control method with nominal flux control method

A consideration on the effect of utilising proposed loss-minimisation control method is carried out on the system of two six- and three-phase motors in this section. Parameters of three-phase and six-phase motors are shown in Tables 1 and 2.

In this investigation, proposed loss-minimisation and nominal flux control methods are compared with each other in terms of copper loss, iron loss and efficiency. In the first case, for different values of load torques, speed of three-phase motor and six-phase motor are 200 and 1400 rpm, respectively. In Fig. 4, efficiency, copper loss, iron loss and phase current as a function of load torque for three-phase motor, six-phase motor and whole of two motors are illustrated. Load torque values of three-phase motor are shown on top axis; and load torque values of six-phase motor are shown on bottom axis in Fig. 4. As illustrated in Fig. 4*b*, up to about 32% improvement in efficiency is obtained in light loads.

In the second case, two methods are compared in different speeds. In this situation, load torque of both of three-phase and six-phase motors is 10 N m. Also, efficiency, copper loss, iron loss and

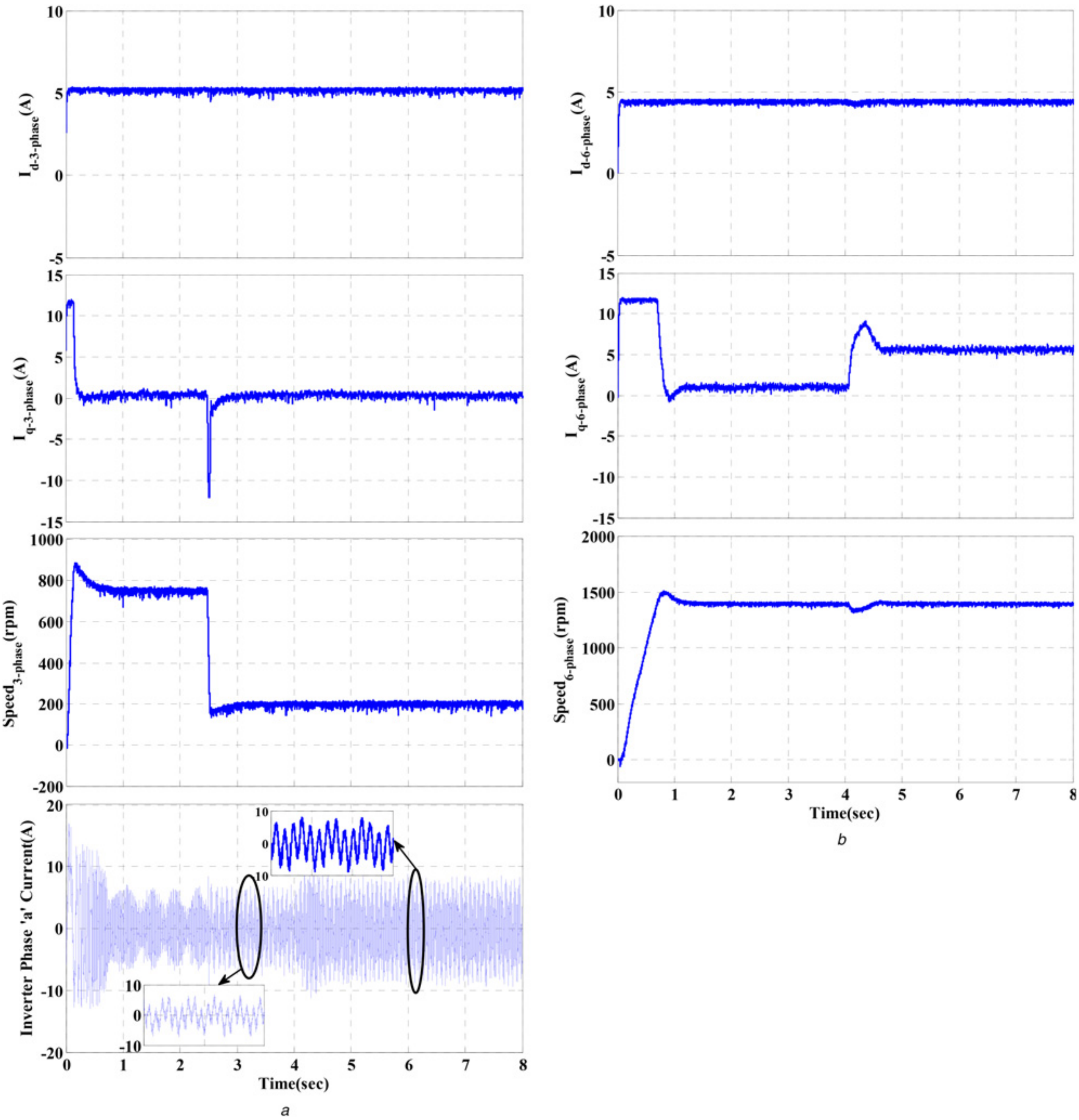

Fig. 7 *Control of two six- and three-phase motors with nominal flux method (experimental result)*
a I_d, i_q and speed of three-phase motor and inverter phase '*a*' current
b I_d, i_q and speed of six-phase motor

phase current as a function of speed for three-phase motor, six-phase motor and whole of two motors are illustrated in Fig. 5. Speed values of three phase motor are shown on top axis; and speed values of six-phase motor are shown on bottom axis in Fig. 5. As illustrated in Fig. 5*b*, up to about 7% improvement in efficiency is obtained using proposed method.

As in nominal flux method, flux level of the motor would be adjusted based on optimum value in nominal speed and load, therefore the difference between efficiency of the methods decreases by increasing the load torque.

6 Experimental results

A laboratory setup is constructed in order to verify proposed method applicability. Test setup configuration and experimental setup are illustrated in Fig. 6. Six- and three-phase motors parameters, incorporated in experimental setup, are listed in Tables 1 and 2. A Microchip dsPIC microcontroller is utilised in experimental setup. As shown in Fig. 6*b*, six-phase motor is coupled to dc generator as load. Results are sampled via an Advantech USB-4711A data acquisition apparatus.

Effectiveness in loss reduction of proposed method in comparison with nominal flux method under different conditions is investigated experimentally. Also motor losses which are obtained via calculation and experimental results are compared with each other for both methods.

In the experimental test, six-phase motor is coupled to dc generator as load; and three-phase motor operates in no-load condition. In this test, three-phase motor accelerates from standstill to 700 rpm, then at $t = 1$ s, motor decelerates to 200 rpm; also six-phase motor accelerates from zero to 1400 rpm; afterwards, a load of 10 N m is applied to motor at about $t = 4$ s.

Results of nominal flux method are shown in Fig. 7; and results of proposed method are shown in Fig. 8 which includes i_q, i_d and

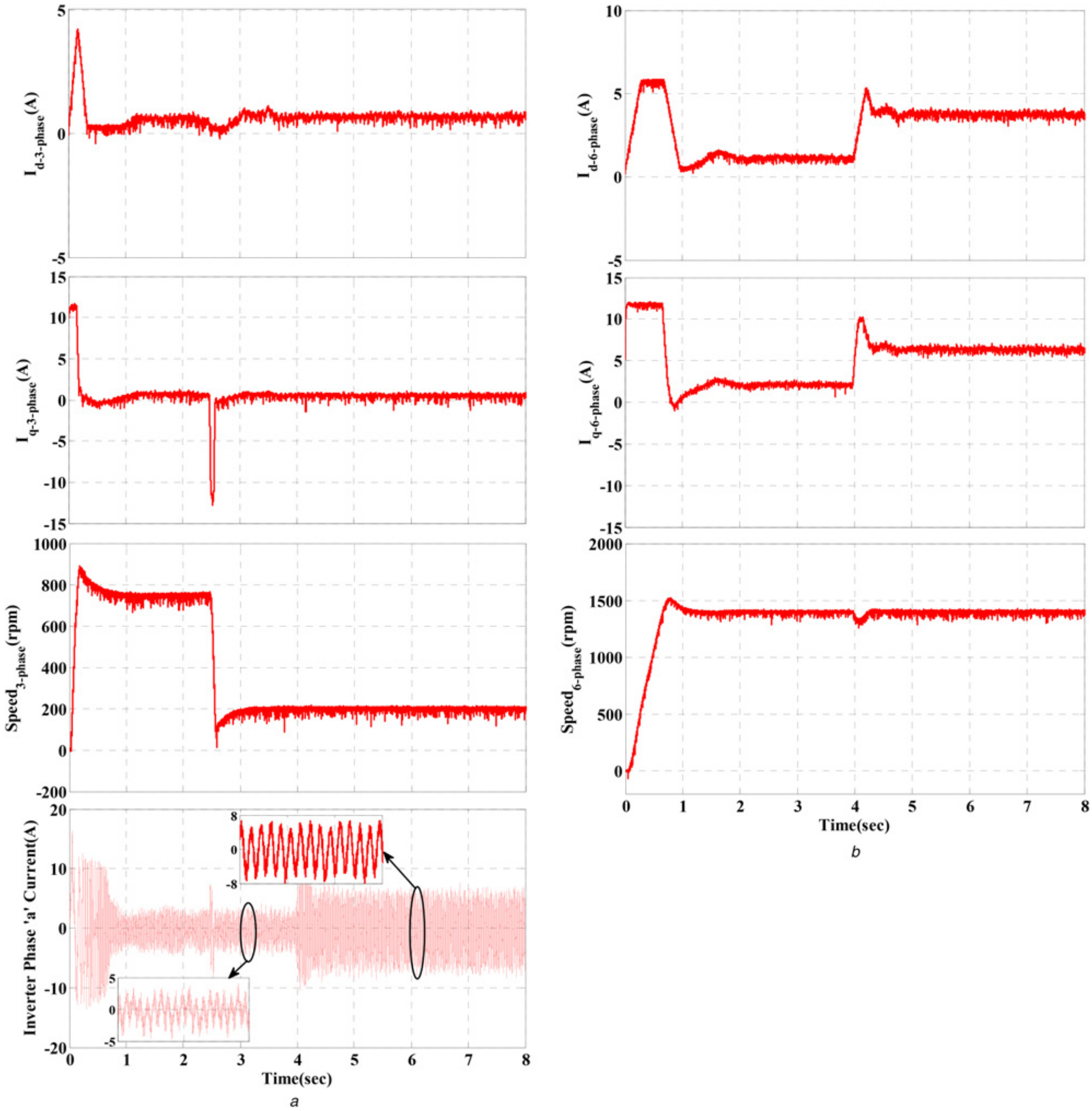

Fig. 8 *Control of two six- and three-phase motors with proposed method (experimental result)*
a I_d, i_q and speed of three-phase motor and inverter phase '*a*' current
b I_d, i_q and speed of six-phase motor

Table 3 Total loss of whole system for both control methods obtained from calculation and experimental results – three-phase motor is no-load; and speed of three-phase motor and six-phase motor are 200 and 1400 rpm, respectively

		Nominal flux method	Proposed method
	calculation	427.3	179.9
$T_{\text{Load-6ph}} = 5$ N m	experimental	434.3	188.4
$T_{\text{Load-6ph}} = 10$ N m	calculation	485.4	293.2
	experimental	494.9	305.6
$T_{\text{Load-6ph}} = 15$ N m	calculation	576.0	407.1
	experimental	589.2	421.3

speed of three- and six-phase motors, and also inverter phase current.

For calculating motor losses in a specified speed and torque, motor steady-state equations are utilised by using i_d, i_q and motor parameters. Also, Table 3 shows motor loss including copper, iron and mechanical losses for both methods obtained from calculation and experiments which have good accordance with each other.

7 Conclusion

In this paper, a method is proposed for loss minimisation of two six- and three-phase drive systems. In two six- and three-phase motor systems, each phase current of three-phase motor comes from two phases of six-phase motor, while currents of six-phase motor do not pass from three-phase motor windings. Therefore, in order to maximum efficiency control of two six- and three-phase motor systems, it is just required to consider extra copper loss produced in six-phase motor, caused by currents of three phase motor in maximum efficiency control of three phase motor, because currents of six-phase motor does not pass through windings of three-phase motor. Therefore, stator resistance of three-phase motor should be considered equal to $\left(R_{s-3\varphi} + (R_{s-6\varphi}/2)\right)$ in maximum efficiency control of three-phase motor, and also stator resistance of six-phase motor should be considered equal to $R_{s-6\varphi}$ in maximum efficiency control of six-phase motor. Also, simulation and experimental results verified effectiveness of proposed method in loss reduction.

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