International Journal on Electrical Engineering and Informatics - Volume 11, Number 1, March 2019

A Hybrid Cross Coupling - Master Slave Technique for Speed Synchronization of Multi PMSMs System Using PID Controller and On-Line Master Selector

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Abstract: Some speed synchronization techniques of multiple electric motors system are well known such as master reference, master slave and cross coupling. The cross coupling technique is only applicable for two motors system whereas the master slave technique can be applied to more than two motors but it provides a poor synchronization performance. This paper offers a hybrid cross coupling - master slave (CC-MS) technique with master selector for angular speed synchronization which can be applied to more than two motors. In order to evaluate performance, this paper also proposes two performance indexes i.e. regulation performance index PI_1 and synchronization performance index PI_2. A proportional integral derivative (PID) controller is equipped at each motor for speed feedback, and the speed coupling between motors is facilitated by a coupling constant. An on-line master selector automatically selects the motor with the largest load as the master when the system is working. Values of the PID controller gains and the coupling constant are determined using the pole placement method. The proposed hybrid CC-MS technique has been evaluated through computer simulations using a vehicle with four permanent magnet synchronous motors (PMSMs) in Matlab-Simulink® environment. The vehicle is simulated moving at a downhill track where the load of four PMSMs drops one by one in sequence. Performance comparison was carried out between the proposed technique and the previously published techniques: master reference and CC-MS without master selector. Simulation results show that the proposed technique gives smaller PI_1 and PI_2 than the other two techniques.

Keywords: cross coupling; master slave; Matlab Simulink; PMSM, speed synchronization

1. Introduction

Drive train components and control with outstanding efficiency are essential, for the reason of approximately 70% of the total energy consumption in electrical transportation or industrial are electric motor [1]. Selection of type, controller and topology for electric motor becomes very important. The PMSM motor is chosen because it offers significant advantages in low inertia, high efficiency, reliability and high energy density (Sebaa, Hassaine, & Ogab, 2017). Multi motors work together to serve huge load in industrial and transportation. Multi motors with single inverter has been used by Kelecy, Matsuse and Jiangbo [2,3,4] for induction motor and by Chiassonet, Fadel and Bidart [5,6,7] for PMSM. In train application, synchronization error between wheels causes slip and skid which in turn leads to wheel damage and energy dissipation. Multi PMSMs with single inverter had different disadvantages based on the used technique. Using master slave technique, only one PMSM was controlled while the others were uncontrolled. Meanwhile by using the average technique, the disadvantage was the controller always take the middle value. Those disadvantages could cause power losses and difficult to apply for vehicle with variable speed control [7].

Multi PMSMs with multi inverters system is chosen due to a better control coordination, can be applied for variable speed control [8] and also has good efficiency [9]. This system requires speed synchronization during acceleration, deceleration and load changes [10]. The existing speed synchronization techniques are master reference, master slave, cross coupling and electronic virtual line shafting (EVLS).

Received: October 22nd, 2018. Accepted: March 23rd, 2019
DOI: 10.15676/ijeei.2019.11.1.11

The master reference control is the most basic uncoupled synchronization technique because each controller gets speed reference respectively so that each motor does not affect each other. Master slave technique feeds speed reference to the master PMSM and then the output speed will become speed reference for the next PMSM (slave PMSM), so a series arrangement enables any disturbance that happens to the master to influence subsequent slaves whereas the variations of a slave cannot give feedback to its master [11]. PMSMs with large moment of inertia are often chosen as the masters. Master slave technique is recommended for industrial application where multi PMSMs operate in sequence and regulation errors are major consideration.

In cross coupling technique, the feedback consist of output speed and relative speed differences between motors. The relative speed differences feedback is multiplied by a weighting gain constant to be regulated rapidly without ripple, and also this feedback makes degree of tightened coupling increase [12]. The disadvantage of cross coupling technique is that it is difficult to extent the arrangement for more than two motors. Zhang *et.al* applied the cross coupling technique to a system with more than two motors by using relative speed differences feedback calculated from adjacent PMSMs [13], while Jianzhong *et.al* also applied the same technique using ring sequential feedback [14]. Those techniques are running well for the system with more than two PMSMs but have calculation complexity.

EVLS technique mimics a mechanical synchronization where mechanical shaft line is replaced by virtual shaft line. EVLS Technique gives speed and position reference signal to each PMSM controller. However, it is not suitable for position control. Mechanical system produce losses 14% higher compared to EVLS technique. Jian li [15] has showed that EVLS has good synchronization performance but quite complex and requires load inertia estimation.

A combination of cross coupling technique and master slave technique has been done in previous research called CC-MS [16]. The CC-MS has tightened coupling as shown by cross coupling technique, and it can also be applied to three PMSM as well as slave master technique. Tuning of proportional, derivative, and integral constants of PID controller used the Ziegler Nichols method while the calculation of feedback using the Routh criterion. Basically, the CC-MS technique is a cross coupling technique, but the relative speed difference is between the angular velocity of the master PMSM and the slaves, which is similar to the master slave technique. The simulation results of the CC-MS technique show excellent maximal overshoot but with moderate synchronization performance and poor regulation performance [16].

This paper proposes a new synchronization technique that is called hybrid CC-MS, where a master selector is added to the original CC-MS system. Therefore, in the hybrid CC-MS every PMSM can act as master and also slave depending on the load. In section 2, mathematical model of PMSM is described. Section 3 presents the proposed hybrid CC-MS synchronization technique. The PID controller constants and the speed coupling feedback gain are calculated using the pole placement method. Control strategy and modulation technique for PMSM are performed by using hysteresis current control. Section 4 reports simulation results and discussion where a performance comparison is done by using performance index measurements. The simulation is conducted using Matlab-Simulink®. Performance comparison is carried out between the proposed technique and the previously published techniques. Finally, conclusion is drawn in section 5.

2. Mathematical model of PMSM

Electrical model of a non salient PMSM can be represent by equation (1) and (2) [17,18].

$$\frac{d}{dt}i_{ds} = \frac{-R_s i_{ds}}{L_s} + \frac{V_{ds}}{L_s} - P\omega_m i_{qs} \tag{1}$$

$$\frac{d}{dt}i_{qs} = \frac{-R_s i_{qs}}{L_s} + \frac{V_{qs}}{L_s} + p\,\frac{\omega_m (L_s i_{ds} + \phi_{af})}{L_s} \tag{2}$$

Electro mechanical model of the PMSM is given by equation (3) and (4).

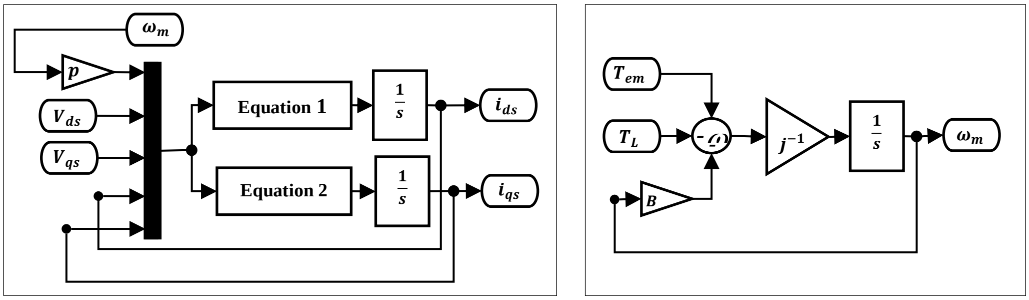
$$\frac{d}{dt}\omega_m = \frac{T_{em} - T_L}{J} - \frac{B}{J}\omega_m \tag{3}$$

$$T_{em} = \frac{3}{2}P \cdot (\phi_{af} i_{qs}) \tag{4}$$

Where:

V_{ds}, V_{qs} Voltage of direct and quadrature axis (volt)
i_{ds}, i_{qs} Current of direct and quadrature axis (amp)
L_s Stator Inductance (H)
R_s Stator Resistance (Ω)
ω_m, ω_e Mechanical and field rotating speed (rad/s)
$\omega_e = p\,\omega_m$
T_{em}, T_L Electromagnetic and load torques (Nm)
J inertia (kgm^2)
P pole pair
B friction coefficient (N.m.s/rad)
Φ_{af} Permanent magnet flux (Wb)

Figures 1(a) and 1(b) show Matlab-Simulink® simulation block diagram of equations (1), (2), and (3), respectively.



(a) (b)

Figure 1. Simulation block diagram of PMSM: (a) electrical model and (b) electro mechanical model

Mathematical model of the PMSM could be presented in a state space form with zero current at direct axis (control properties $i_{sd} = 0$) by equation (5):

$$\begin{bmatrix} \dot{i}_{qs} \\ \dot{\omega}_m \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s} & -\frac{p\phi_{af}}{L_s} \\ \frac{p\,\phi_{af}}{J} & -\frac{B}{J} \end{bmatrix} \begin{bmatrix} i_{qs} \\ \omega_m \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} \\ 0 \end{bmatrix} V_{qs} - T_L \begin{bmatrix} 0 \\ \frac{1}{j} \end{bmatrix} \tag{5}$$

and the speed as an output could be expressed as equation (6):

$$y = [0 \quad 1] \begin{bmatrix} i_{sq} \\ \omega_m \end{bmatrix} \tag{6}$$

From equations (5) and (6) a transfer function is obtained as given by equation (7):

$$G(s) = \frac{\omega_m(s)}{V_{qs}(s)} = \frac{b_o}{s^2 + a_1 s + a_o} \tag{7}$$

Hysteresis current control is used as control strategy. Hysteresis current control PWM is a current control feedback method of PWM, where the actual current continually tracks the command current within a hysteresis band. Figure 2 shows a block diagram of PMSM model at Matlab-Simulink®. There are two main blocks those are a block for the electrical model and a block for the electro mechanical model.

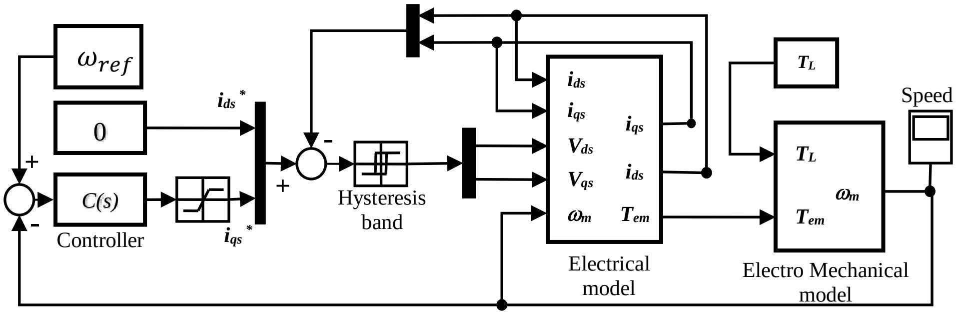


Figure 2. Simulink model for single PMSM with Hysteresis current controller

3. Proposed Synchronization Technique

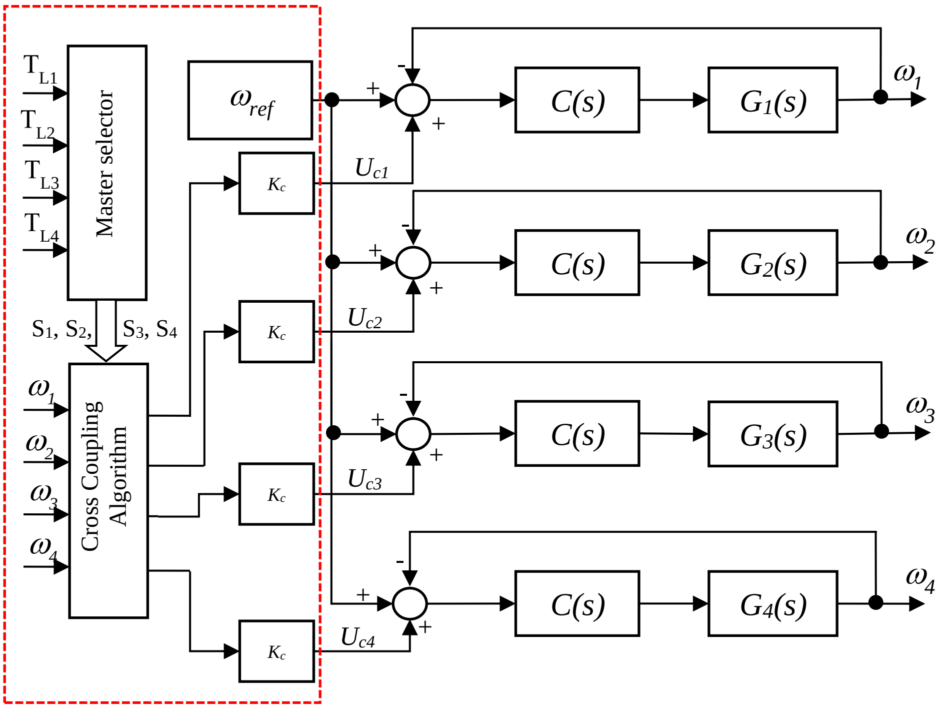


Figure 3. Proposed synchronization technique

In this paper, a master selector is added to the CC-MS system in order to improve performance (red box with dashed line in Figure 3). The PMSM with the largest load is selected as a master. The master selector block compares all loads, where T_{L1}, T_{L2}, T_{L3} and T_{L4} act as inputs. The master selector find the largest load from the inputs using min-max function block, but it only has one output which is the largest value. To determine the largest value belong to who, the output from the min-max function compared to each load. The output of the master selector block is the input state for the cross coupling algorithm (S_1, S_2, S_3 and S_4). The input state is 1 for the state of the master and 0 for the slave. In one time there is only a state value of 1 and three state values of 0.

The coupling constant K_c for relative speed differences feedback between master PMSM and slave PMSMs needs to be calculated in the proposed synchronization technique. K_c is positive real number and U_{ci} is value for speed coupling feedback. Speed coupling feedback values for master and slave are calculated by equation (8a) and (8b).

$$U_{ci} = K_C(\omega_j - \omega_i)\text{, } i := \text{slave, } j := \text{ master, state} := 0 \tag{8a}$$

$$U_{ci} = K_C(-\omega_i + \frac{1}{3}K_C \sum_{j=1}^{3} \omega_j)\text{, } i := \text{master, } j := \text{ slave, state} := 1 \tag{8b}$$

Where U_{ci} is the feedback of speed coupling, and $i \neq j$.

The probability of value i is three of 1,2,3,4 while j is equal to one of the values not i. The coupling constant K_c and the controller $C(s)$ are designed in order to give good regulation performance and synchronization performance, while keeping the system stability. The control topology of each PMSM can be expressed in figure 4. ω_{ref} is the main reference and ω^* is an internal reference.

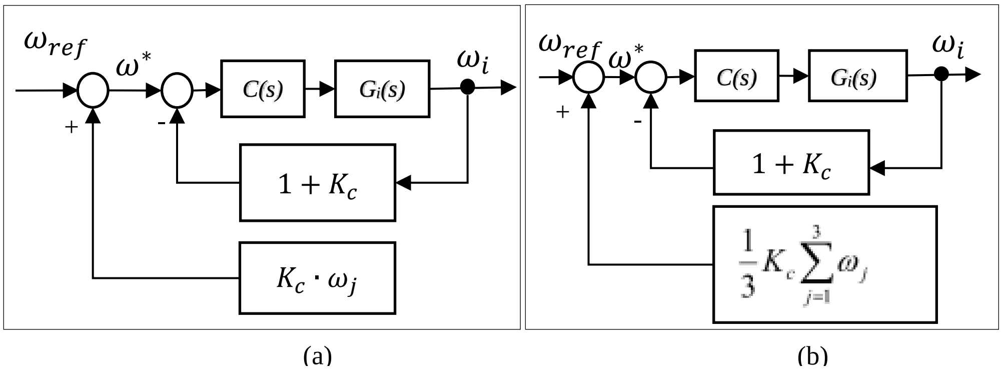


Figure 4. Block diagram of closed loop PMSM: (a) for slave and (b) for master

G(s) is transfer function of each PMSM that is given by equation (7). $C(s)$ is a PID controller with a transfer function given by equation (9).

$$C(s) = \frac{K_d s^2 + K_p s + K_i}{s} \tag{9}$$

(K_p, K_i, K_d**)** are the proportional, integral, and differential gains. The close loop transfer function from internal reference ω^* to angular speed ω_i from Figure 4 is given by equation (10).

$$T(s) = \frac{\omega_i(s)}{\omega^*(s)} = \frac{(K_d s^2 + K_p s + K_i)\cdot b_o}{s^3 + a_1 s^2 + a_o s + (K_c + 1)(K_d s^2 + K_p s + K_i)\cdot b_o} \tag{10}$$

The pole placement is used to determine the PID controller gains and the coupling constant values. In the generic form the performance characteristics of transfer function at equation (11) is adopted [19].

$$T_m(s) = \frac{(K_d s^2 + K_p s + K_i)\cdot b_o}{(s + \alpha\cdot\omega_n)(2\cdot\zeta\cdot\omega_n\cdot s + \omega_n^2)} \tag{11}$$

When a single motor is used, integral absolute error is commonly used as a regulation performance [20]. Since four motors are used, this paper proposes regulation and synchronization performance indexes as given in equation (12) and (13).

$$PI_1 = \int_0^{tf} \sqrt{\frac{1}{4} \sum_{i=1}^{4} e_i{}^2}\, dt = \frac{1}{2} \int_0^{tf} \sqrt{\sum_{i=1}^{4} (\omega_{reff} - \omega_i)}\, dt \tag{12}$$

$$PI_2 = \int_0^{tf} (\omega_{\max} - \omega_{\min})\, dt \tag{13}$$

Where:

PI_1 Regulation performance index
PI_2 Synchronization performance index
i 1,2,3,4
$\omega_{min}(t)$ the lowest angular speed among all the PMSMs at time t.
$\omega_{max}(t)$ the highest angular speed among all the PMSMs at time t.

4. Simulation result and discussion

Evaluation of multi-motors system is done by simulating a vehicle in a downhill track where the four PMSM loads drop one by one in sequence. Load disturbance step function for each PMSM occurs at different time, and the timing are $PMSM_1$ at 0.8 second, $PMSM_2$ at 0.6 second, $PMSM_3$ at 0.4 second and $PMSM_4$ at 0.2 second. Computer simulations were conducted in Matlab-Simulink® environment, and the simulation results are output speed in revolutions per minute (RPM). The PMSM parameters values are the same for all four motors and table 1 are the parameters used in the simulation.

Table 1. PMSM Parameter

Parameter	**Value (unit)**
R_s – stator Resistance	2,875 (Ω)
$\square_{af}$ –magnet permanent flux	0,75 (Wb)
B –friction coefficient	0,0002 (N.m.s/rad)
L_s –stator inductance (for d and q axis)	0,0085 (H)
P – pole pairs	4
J –motor inertia	0,0008 (Kg.m^2)

By substituting the PMSM parameters values in table 1, the state space model in equation (6) becomes (14).

$$\begin{bmatrix} \dot{i}_{qs} \\ \dot{\omega}_{mech} \end{bmatrix} = \begin{bmatrix} -337{,}5 & -82{,}35 \\ 875 & -0{,}25 \end{bmatrix} \begin{bmatrix} i_{qs} \\ \omega_{mech} \end{bmatrix} + \begin{bmatrix} 117{,}65 \\ 0 \end{bmatrix} V_{qs} - \begin{bmatrix} 0 \\ 1250 \end{bmatrix} T_L \tag{14}$$

The transfer function in equation (7) and the close loop transfer function in equation (10) now become equation (15) and (16), respectively:

$$G(s) = \frac{10294375}{s^2 + 337.75 \cdot s + 72490625} \tag{15}$$

$$T_m(s) = \frac{(K_d \cdot s^2 + K_p \cdot s + K_i) \cdot 10294375}{s^3 + 337.75 \cdot s^2 + 72490625 \cdot s + (K_c + 1)(K_d \cdot s^2 + K_p \cdot s + K_i) \cdot 10294375} \tag{16}$$

After several trial and error through computer simulations, natural frequency □n, dumping ratio ζ, α, and the coupling constant K_c are selected equal to 700 rad/sec, 0.77, 1, and 1.5, respectively. The performance characteristics in equation (11) now becomes that in equation (17).

$$T_m(s) = \frac{(K_d \cdot s^2 + K_p \cdot s + K_i) \cdot 10294375}{s^3 + 1778 \cdot s^2 + 1244600\, s + 343000000} \tag{17}$$

From equation (16) and (17), the following PID controller gains are obtained: K_p = 4.556, K_i = 1332.76, K_d = 0.0056.

In the simulation the speed reference is 1500 rpm and in one second duration where the load drop one by one every 0.2 second, the result as shown in figure 5 is four PMSMs speed synchronization using CC-MS without master selector. All PMSMs have the same loads so that angular speed for all PMSMs are coincide and no regulation error exists as long as the load is unchanged. Inset in Figure 5 is $PMSM_1$ apply as master PMSM where black line is $PMSM_1$ and the red line is $PMSM_2$, $PMSM_3$, and $PMSM_4$. Peak of angular speed regulation error is 31 rpm and the regulation error occurs during 0.04 second.

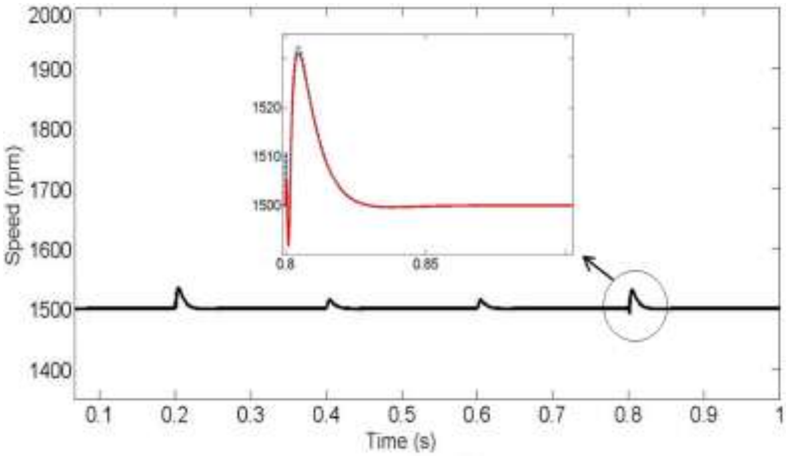


Figure 5. Simulation result using CC-MS without selector
(inset is speed during load change) [16]

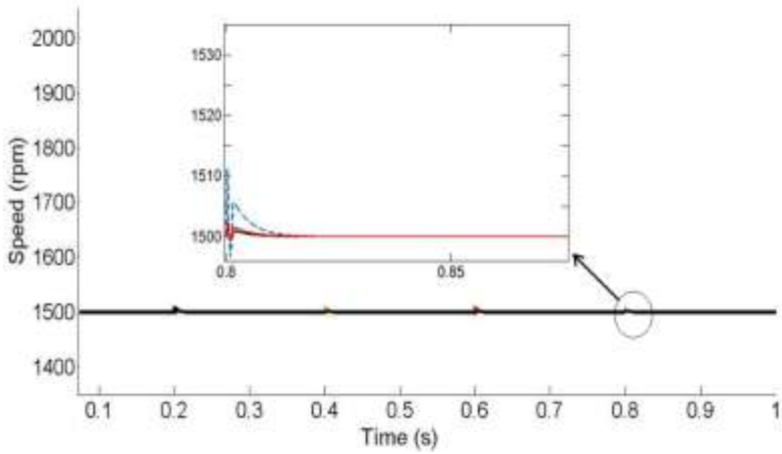


Figure 6. Simulation result using the proposed hybrid CC-MS technique
(inset is the speed during load change)

Figure 6 is simulation result for multi PMSMs with master selector. All PMSMs have the same loads so that angular speeds for all PMSMs are coincide and there almost no regulation error as long as the load is unchanged. The dashed blue line and the red line shown in the inset Figure 6 is $PMSM_1$ and $PMSM_4$, respectively. The black solid lines are the coincide lines for $PMSM_2$ and $PMSM_3$. $PMSM_4$ acts as the master PMSM when the load at $PMSM_1$ is dropped. Peak angular speed regulation error is 11 rpm and the regulation error occurs during 0.02 second.

Figure 7 shows synchronization performance indexes, which is 7 (a) indicates that without master selector the peak of synchronization error during load change is 11 rpm. Figure 7 (b) shows that with master selector the peak of synchronization error during load change is also 11 rpm but with shorter duration.

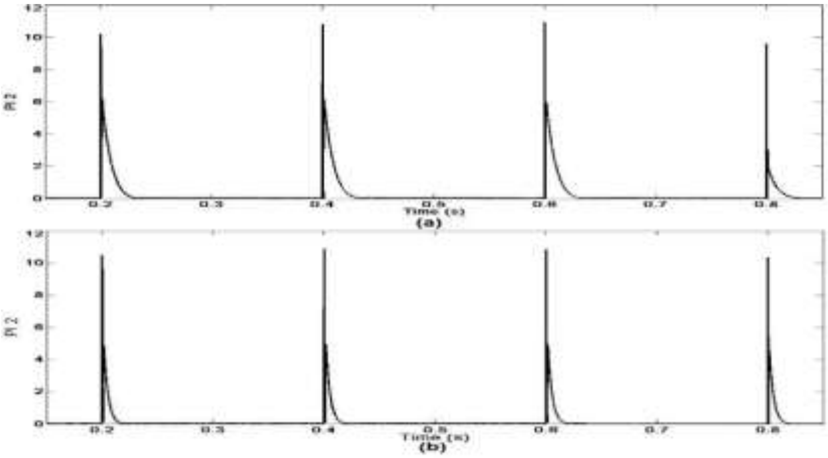


Figure 7. Synchronization performance indexes: (a) without selector and (b) with selector

Figure 8 shows regulation performance indexes, whereas 8 (a) indicates that without master selector the peak of regulation error during load change is 16 rpm, and figure 8 (b) shows that with master selector the peak of regulation error during load change is consistently 3 rpm.

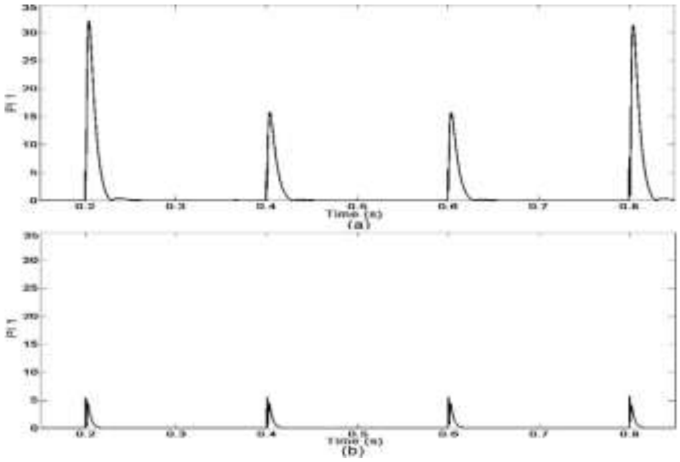


Figure 8. Regulation performance indexes: (a) without selector and (b) with selector

Table 2. Performance comparison

Parameters	Proposed technique	Previous technique [16]	Master reference technique
Regulation performance index (PI_1)	0.07119	0.9678	0.07553
Synchronization performance index (PI_2)	0.1118	0.1804	0.1489
Peak of regulation error under load change at time 0.8 s	11 rpm	31 rpm	11 rpm

Performance comparison between the hybrid CC-MS synchronization technique and the master reference synchronization technique was also performed. The simulation for master reference synchronization used the block diagram in figure 3, but the coupling constant is zero and the PID controller were re tuned.

Table 2 shows the performance comparison between the master reference, the system without master selector (using the CC-MS technique which was previously published) and the system with master selector (the proposed hybrid CC-MS technique). Despite showing the same peak values, the synchronization performance index shows lower values for the system with the selector than the system without selector and the master reference technique. This may be caused by a shorter duration for system synchronization errors with the selector rather than system without selector (Figure 7 (a) and Figure 7 (b)). The regulation performance index shows a lower value for the system with master selector than the system without master selector and the master reference technique. This may be caused by peak performance index error when the load changes. The performance index error of the system with master selector (figure 8 (b)) is much lower than the system without selector (figure 8 (a)). Performance indexes for synchronization and regulation of the master reference technique show lower values than system without master selector but still higher than the system with the master selector.

5. Conclusion

This paper has presented a hybrid CC-MS technique for speed synchronization of PMSMs with on line master selector. Simulation results show that the proposed method can be applied for synchronization of four PMSMs with good performance: fast recovery time, very small regulation error and small synchronization error when there is load change. The regulation performance index for the system with the selector is close to one tenth of the system without selector while the synchronization performance index for the system without selector is fifty percent higher than the system with the selector. The regulation performance index for the master reference technique is ten percent higher than the system with the selector while the synchronization performance index for the system with the selector is close to three quarters of the master reference technique.

6. Acknowledgment

The author would like to thank LPDP and all colleagues for helping in simulation control at Electrical Energy Conversion Laboratory - ITB also all co-worker at Research Centre for Electrical Power and Mechatronics - LIPI.

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