Hybrid Modeling and Applications of Virtual Metro Systems

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***Abstract*- Considering both electrical and mechanical parameters of metro systems, a hybrid modeling method is proposed to develop a virtual metro system (VMS), which consists of traction power supply module, route module, resistance module and vehicle module. The characteristic parameters of the proposed modules are verified by real metro systems. Compared with conventional electric traction control strategies for metro vehicles, the proposed VMS can provide a virtual environment, which makes the simulation more close to real situations. Consequently, the electric traction control strategy verified by VMS can be easily applied to real metro vehicles. Applications of VMS confirm the effectiveness to the development of control strategy for metro vehicles.**

I. INTRODUCTION

Due to the excessive release of CO_2, greenhouse effect has become critical and received worldwide attention. On the other hand, traffic congestion is globally existed, which has obviously increased the time cost during urban travel, especially in major cities. Due to the advantages of high speed, punctuality and environment protection, urban mass transit, especially metro, is taken into account to meet the two proposed world challenges above. Generally, metro is a multidisciplinary subject which covers broad and complex aspects including some core components, such as metro vehicle. As is well known, the development of metro is strongly dependent on the performance of metro vehicles, and modern metro vehicle is usually a high power AC drive system. Considering complexity and cost, the performance of metro vehicle must be ensured before production, while it is difficult and expensive to carry out real experiments.

With the development of computer techniques, digital computer simulation of rail transit system has been widely adopted as a standard computer-aided engineering tool during the design and development stages of existing and new rail transit systems [1], and different simulation methods of rail transit system have been presented [2]-[19]. The applications of rail transit simulation system can be classified as simulation of train movement [2]-[9], calculation of traction power supply systems [10]-[13] and the generation of train time schedules [14]-[19]. Train movement is based on the calculation of the speed and distance profiles when a train is traveling from one point to another according to the limitations imposed by the signaling system and traction drive characteristics [4]. Traction power supply systems are physically huge electrical circuits with time-varying and moving loads [12]. The generation of train time schedules in metro lines corresponds to obtaining the dwell time at stations, run time between stations and the dispatch time of trains according to the variation of passenger demand along train trajectories [16]. The simulation environment of railroad has been discussed in [20] and an electromechanical model for high-speed train is proposed in [21].

However, the electric traction systems are usually simplified as traction efforts or traction characteristics [4], [13], [15], [21], and the control strategies of electric traction for metro through rail transit simulation system have not been reported, which is exactly the purpose of this paper. In this paper, a simulator, VMS, with hybrid modeling method is developed. In section II, the hybrid modeling method is proposed, in which both electrical and mechanical parameters of metro systems are considered. Based on the proposed method, VMS is developed based on Matlab/Simulink platform, which provides a virtual environment for investigation on the electric traction control strategies of metro vehicle and promotes the simulations to system-level. To verify the effectiveness of VMS, an application is carried out in section III. Finally, some conclusions are drawn in Section IV.

II. HYBRID MODELING OF VMS

A real metro system usually consists of traction power supply system, metro vehicle and route, as shown in Fig.1. Considering all of these subsystems, a developed VMS includes four key modules, namely, traction power supply, route, resistance, and vehicle. The characteristic parameters of the proposed modules are verified by real metro systems. Each module is presented as follows and then integrated into a whole VMS.

A. Module Description

1. Traction Power Supply (TPS) Module

In the early stage, both AC and DC TPS systems were adopted [22]. However, with the improvement of power electrics and control theory, DC-TPS are more popular than AC-TPS in modern metro systems. Therefore, DC-TPS is adopted as the prototyped module in the developed VMS. Considering the core task of VMS is to investigate electric traction control strategies, TPS module is simply modeled by

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a three-phase AC voltage source and a high power uncontrolled rectifier, as shown in Fig.2.

2. *Route Module*

As a major style of urban mass transit, the running environment of metro vehicle is usually underground. Considering the complicated conditions of ground surface and cost saving, more restrictive design requirements of metro lines are demanded, which complicate the running condition of metro vehicle. During the real driving procedure, the movement of train is under the constraints of track geometry [1]. Consequently, an accurate route module is important to VMS. Therefore, a database containing real route parameters is set up. Considering the gradient of ramps has a great influence in running resistance, while the radius of curves limits the running speed, both the proposed parameters are stored in the database. Data stored types are illustrated in Fig. 3. When VMS is running, data stored in route module is looked up by the space distance of metro vehicles.

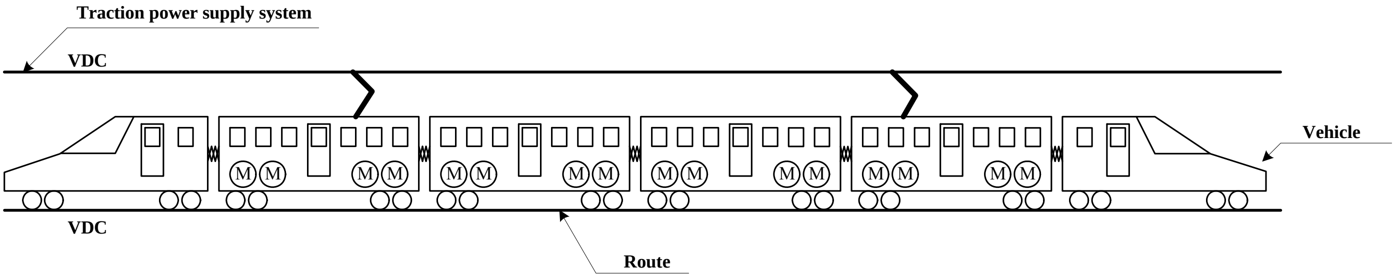


Fig. 1. The structure of a real metro system

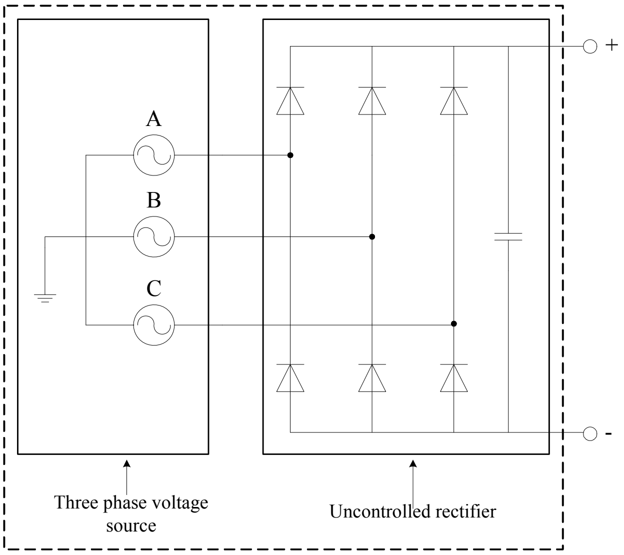
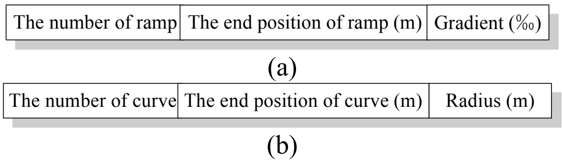


Fig. 2. The structure of traction power supply module.



The number of ramp	The end position of ramp (m)	Gradient (‰)

(a)

The number of curve	The end position of curve (m)	Radius (m)

(b)

Fig. 3. (a) Data stored type of ramps (b) Data stored type of curves

3. *Resistance Module*

The running resistance of metro vehicle is always existed, which is mainly effected by the air and route parameters. During real driving procedure, metro vehicle bears running resistance, which can be mainly divided into three components, i.e., air resistance, ramp resistance and curve resistance. Air resistance is closely relative with specific metro vehicle. The resistance formulas for the vehicle in this paper are shown as follows:

$$f_{air} = \frac{6.4M + 130000N_{motor} + 0.504vM + sv^2\left[596.16 + 125.19\left(N_{car} - 1\right)\right]}{1000} \tag{1}$$

$$f_r = MgG_r / 1000 \tag{2}$$

$$f_c = \begin{cases} 0 \\ 0.7Mg / R_c \end{cases} \tag{3}$$

$$f = f_{air} + f_r + f_c \tag{4}$$

where，

f running resistance,
f_{air} air resistance,
f_r ramp resistance,
f_c curve resistance,
v running speed of metro vehicle,
M total mass of metro vehicle,
N_{motor} traction motor amount,
N_{car} car amount,
G_r gradient of ramp,
s front window area of metro vehicle,
g acceleration of gravity,

R_c radius of curve.

The running resistance is treated as the load torque as shown by:

$$T_{load} = \frac{fv}{N_{motor}\omega} \tag{5}$$

where，

ω angular velocity of traction motor,

T_{load} load torque of traction motor.

4. *Vehicle Module*

As is shown in Fig.4, vehicle module is divided into two subsystems: rotational motion subsystem and linear motion subsystem, which are connected through a data interface. Rotational motion subsystem includes electromagnetic torque of traction motor T_e, load torque T_{load}, equivalent inertia of metro vehicle J and ω. Linear motion subsystem contains traction effort of metro vehicle F, f, M, v, and the space position x. Vehicle module is composed of 7 components: braking resistor, inverter, traction motor, gearbox, wheel, sensor and controller, as illustrated in Fig.5. To reduce the amount of calculation, the real traction motors are equivalently represented by only one traction motor in vehicle module.

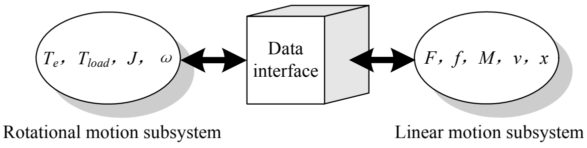


Fig. 4. Two subsystems of vehicle module

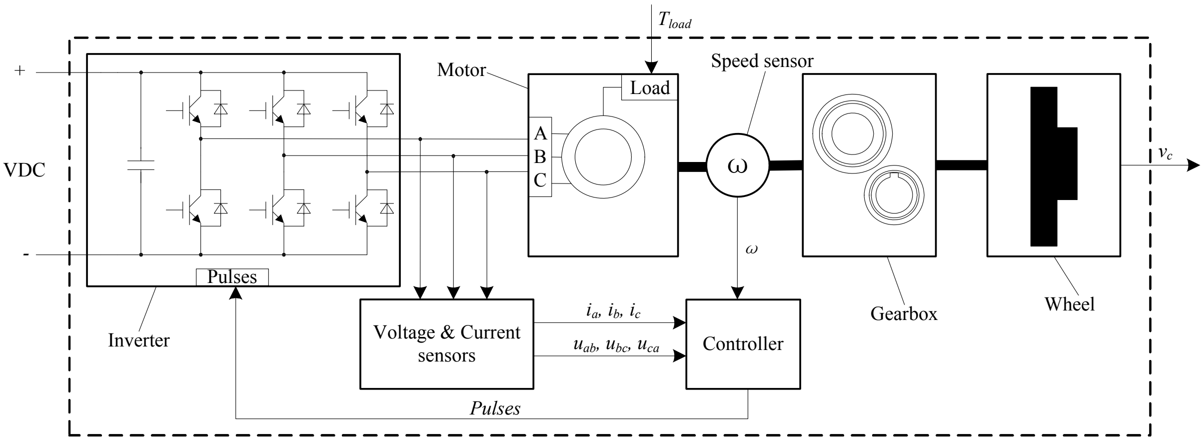


Fig. 5. The block diagram of vehicle module

The mass of vehicle considering passengers is converted to the inertia of traction motor by energy conservation, which is presented as:

$$J = \frac{M}{N_{motor}}(\frac{v}{\omega})^2 \tag{6}$$

$$v = \frac{\omega d_w}{2\delta} \tag{7}$$

where

d_w wheel diameter,

δ gearbox ratio.

Controller is the core of VMS. Comparing with traditional electric drive control strategies for metro vehicles, VMS can provide the more real environment. The control strategy of the electric traction system is implemented in controller (shown in Fig. 6) with input signals of phase currents (i_a, i_b, i_c), line voltages (u_{ab}, u_{bc}, u_{ca}) and v. Switching pulses are generated to control the inverter. In 1986, direct torque control (DTC) was proposed [23]. Due to the advantages of quick response, robustness and low switching frequency, DTC has attracted a lot of attention and was firstly applied in rail transit in 1988 [24]. In this paper, DTC is adopted and the control schemes of DTC is shown in Fig. 6.

B. *System Integration*

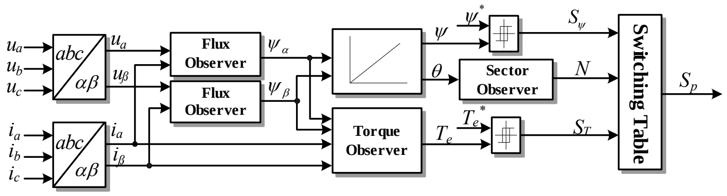


Fig. 6. The control schemes of DTC

Finally, a integrated VMS by the proposed four modules is shown in Fig. 7.

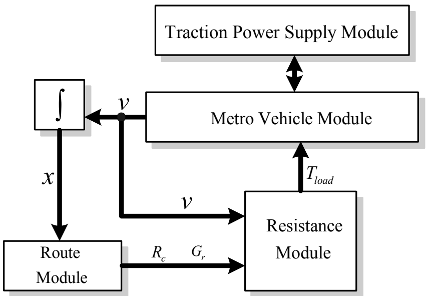


Fig. 7. The integration diagram of VMS

III. VERIFICATION OF VMS

In order to verify the effectiveness of VMS, a tested metro line (TML) is structured and a simulation is carried out based on it.

A. *Parameter Setting*

The metro vehicle style is illustrated in Fig.1, and its parameters are shown in TABLE I. The parameters of TML are described in both TABLE II and TABLE III. From TABLE III, J can be calculated by (6) and the result is treated as the inertia of traction motor.

TABLE I
METRO VEHICLE PARAMETERS

Traction motor	Stator resistance R_1	0.143 Ω
	Rotor resistance R_2	0.0745 Ω
	Stator self-inductance L_{11}	0.946 mH
	Rotor self-inductance L_{22}	1.2 mH
	Mutual inductance L_m	37.1 mH
	Fiction factor η	0.148 N•m•s
	Pole pairs p	2
	Rated power P_e	250 kW
Gear	Ration σ	6.9
Power supply mode	DC voltage U_{dc}	1500 V
Wheel	Radius d_w	0.805 m
Total mass of vehicle M		337600 kg
Traction motor amount N_{motor}		16
Car amount N_{car}		6
Front window area of vehicle s		10.2 m^2
Max speed V_{max}		80 km/h

TABLE II
CURVE PARAMETERS OF TML

The number of curve	The end position of curve (m)	Radius[a] (m)
1	224.19	8000.00
2	314.52	500.00
3	378.60	8000.00
4	700.00	400.00

[a] Radius 8000.00 m is used to represent straight metro line

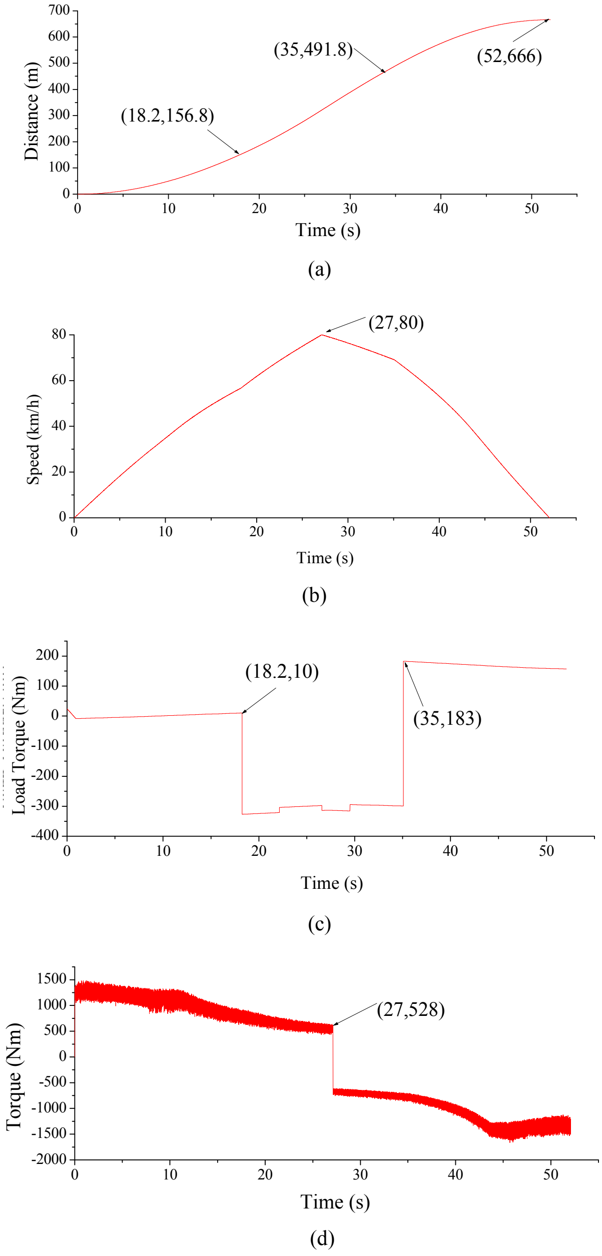
TABLE III
RAMP PARAMETERS OF TML

The number of ramp	The end position of ramp (m)	Gradient (‰)
1	156.79	-2
2	491.79	-30
3	700.00	10

B. *Simulation*

In the simulation, the metro vehicle traveled along TML and the metro vehicle was expected to reach the maximum speed 80 km/h and then stop. The performances of the proposed metro vehicle are shown in Fig. 8.

From Fig. 8(a), it can be seen that the whole tested distance is 666 m. In Fig. 8(b), the speed is firstly increased to V_{max} at t=27s, and the vehicle is stopped at t=52s. Due to the existence of ramps, sudden jumps of load torque occurred at t=18.2s and t=35s as shown in Fig. 8(c), which results the corresponding changes of acceleration. Addtionally, regeneration braking is adopted ,which can be seen in Fig. 8(d). The waves of DC voltage and phase current of traction motor are shown in Fig. 8(e) and Fig. 8(f), respectively.

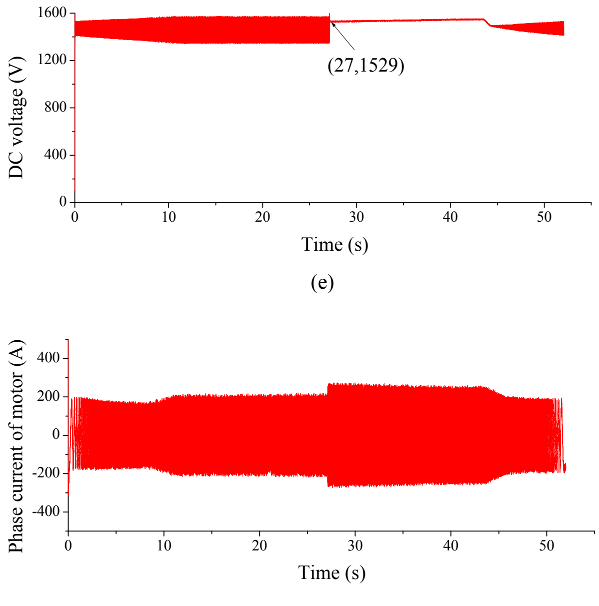


(a)

(b)

(c)

(d)



(e)

(f)

Fig. 8. Simulation Results (a) Distance (b) Speed (c) Load torque (d) Torque (e) DC voltage (f) Phase current of motor

IV. CONCLUSION

In this paper, a hybrid modeling method considering both electrical and mechanical parameters is proposed and a virtual metro system is developed. The simulation is carried out and the results verify the effectiveness of VMS.

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REFERENCES

[1] C. J. Goodman, L. K. Siu, and T. K. Ho, “A review of simulation models for railway systems,” in *Proc. IEE Developments in Mass Transit Systems Conf.*, 1998, pp. 80-85.

[2] B. Mellitt, C. J. Goodman, and R. I. M. Arthurton, “Simulator for studying operational and power-supply conditions in rapid-transit railways”, *Proc. Inst. Electr. Eng.*, vol. 125, no. 4, pp. 298-303, Apr. 1978.

[3] E. Khmelnitsky, “On an optimal control problem of train operation,” *IEEE Trans. Autom. Control*, vol. 45, no. 7, pp. 1257-1266, Jul. 2000.

[4] T. K. Ho, B. H. Mao, Z. Z. Yuan, H. D. Liu, and Y. F. Fung, “Computer simulation and modeling in railway applications,” *Comput. Phys. Commun.*, vol. 143, no. 1, pp. 1-10, Feb. 2002.

[5] K. P. Li, Z. Y. Gao, and B. Ning, “Cellular automaton model for railway traffic,” *J. Comput. Phys.*, vol. 209, no. 1, pp. 179-192, Oct. 2005.

[6] K. P. Li, Z. Y. Gao, and B. H. Mao, “Energy-optimal control model for train movements,” *Chin. Phys.*, vol. 16, no. 2, pp. 359-364, Feb. 2007.

[7] Y. Bavafa-Toosi, C. Blendinger, V. Mehrmann, A. Steinbrecher, and R. Unger, “A new methodology for modeling, analysis, synthesis, and simulation of time-optimal train traffic in large networks,” *IEEE Trans. Autom. Sci. Eng.*, vol. 5, no. 1, pp. 43-52, Jan. 2008.

[8] M. Abril, F. Barber, L. Ingolotti, M. A.. Salido, P. Tormos, and A.. Lova, “An assessment of railway capacity,” *Transp. Res. Pt. e-Logist. Transp. Rev.*, vol. 44, no. 5, pp. 774-806, Sep. 2008.

[9] F. Lu, G. H. Tian, X. L. Li, and M. M. Song, “The calculation and simulation to the subway train's time interval,” in. *Proc. IEEE Int. Conf. Autom. Logist.,* 2008, pp. 1956-1959.

[10] S. N. Talukdar, and R. L. Koo, “The analysis of electrified ground transportation networks,” *IEEE Trans. Power App. Syst.*, vol. 96, no. 1, pp. 240-247, Jan./Feb. 2007.

[11] Y. C. Liu, and J. F. Chen, “Control scheme for reducing rail potential and stray current in MRT systems,” *IEE Proc., Electr. Power Appl.*, vol. 152, no. 3, pp. 612-618, May 2005.

[12] T. K. Ho, Y. L. Chi, J. Wang, K. K. Leung, L. K. Siu, and C. T. Tse, “Probabilistic load flow in AC electrified railways,” *IEE Proc., Electr. Power Appl.*, vol. 152, no. 4, pp. 1003-1013, Jul. 2005.

[13] Q. Z. Wan, J. Y. Chen, Z. H. Huang, and Z. J. W., “Real-time tracking of substation's feeder current based on traction calculation,” in *Proc. 2nd IEEE Conference on Industrial Electronics and Applications*, 2007, pp. 777-782.

[14] V. V. Breusegem, G. Campion, and G. Bastin, “Traffic modeling and state feedback control for metro lines,” *IEEE Trans. Autom. Control*, vol. 36, no. 7, pp. 770-784, Jul. 1991.

[15] D. C. Gill and C. J. Goodman, “Computer-based optimisation techniques for mass transit railway signalling design,” *IEE Proc., Electr. Power Appl.*, vol. 139, no. 3, pp. 261-275, 1992.

[16] W. O. Assis and B. E. A. Milani, “Generation of optimal schedules for metro lines using model predictive control,” *Automatica*, vol. 40, no. 8, pp. 1397-1404, Aug.2004.

[17] J. Tornquist and J. A. Persson, “N-tracked railway traffic re-scheduling during disturbances,” *Transportation Research Part B: Methodological*, vol. 41, no. 3, pp. 342-362, 2007.

[18] E. Castillo, I. Gallego, J. M. Ureña, and J. M. Coronado, “Timetabling optimization of a single railway track line with sensitivity analysis,” *TOP*, vol. 17, no. 2, pp. 256-287, Dec. 2009.

[19] T. Albrecht, “Automated timetable design for demand-oriented service on suburban railways,” *Public Transport*, vol. 1, no. 1, pp. 5-20, May 2009.

[20] H. Krueger, E. Vaillancourt, A. M. Drummie, S. J. Vucko, and J. Bekavac, “Simulation within the Railroad Environment,” in *Proc. Winter Simulation Conf.,* 2000, pp. 1191-1200.

[21] S. Leva, A. P. Morando, and P. Colombaioni, “Dynamic analysis of a high-speed train,” *IEEE Trans. Veh. Technol.*, vol. 57, no. 1, pp. 107-119, 2008.

[22] R. J. Kemp, “Developments in electric traction,” *Power Eng. J.*, vol. 3, no. 2, pp. 71-82, Mar.1989.

[23] I. Takahashi and T. Noguchi, “A new quick-response and high-efficiency control strategy of an induction motor,” *IEEE Trans. Ind. Appl.*, vol. IA-22, no. 5, pp. 820-827, /9.

[24] M. Depenbrock, “Direct self-control (DSC) of inverter-fed induction machine,” *IEEE Trans. Power Electron.*, vol. 3, no. 4, pp. 420-429, Oct.1988.

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