Circulation Current Reduction for a Motor Simulator System using a Power Converter with a Common Mode Transformer

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***Abstract*-This paper presents a new suppression method of circulation current for a motor simulator system. A conventional system requires a large transformer at grid frequency to avoid a circulation current between the motor simulator and a test inverter, besides a regenerative converter is required too. In the proposed topology, the high frequency components of the circulation current are suppressed by a common mode transformer, and the low frequency components are suppressed by zero phase current control. Furthermore, a small size medium frequency common mode transformer is used instead of the regenerative converter and the grid frequency transformer. In addition, the proposed system can simulate the transient condition of the motor. The proposed method is validated based on the simulation and experimental results. The motor simulator primary current waveform agrees well with that of the actual motor, including the distortion due to a voltage error by a dead time period. Also the low frequency component of the circulation current was suppressed to less than 1% of the fundamental component by using the proposed method.**

I. Introduction

Recently, the development of systems using special and specific motors that have very high or low speed rating for applications of hybrid electric vehicles, micro gas turbines and wind power generators etc., have been extensively studied Such a special motor is driven using an inverter. Therefore, in order to evaluate an inverter system, the special motor is required as the load. However, these special motors have spent a long time in development, so that inverter evaluation has had to wait until completion of the special motor development; therefore, the development period for the inverters is required to be as short as possible [1-5].

Therefore, to achieve a shorter development period, a passive load consisting of resistors and reactors is used as a simulator in place of the special motor. The basic operation of the inverter can be confirmed by the passive load; however, the detail of the control algorithm and the reliability of the inverter main circuit under various operations can not be evaluated. In addition, the large power is required to be consumed by load resistances.

On the other hand, a motor simulator, which is realized by controlling a power converter instead of the actual motor or R-L load, has been reported [6, 7]. The current command of the power converter is given by a voltage current differential equation of load characteristics. The motor simulator is very useful, because it can achieve various load conditions by changing only the equation. Therefore, since the motor simulator perform the compact size of a test bench to require no load machine and the inverter, which control the load torque or speed of the load machine. In addition, the output power of the test inverter can be regenerated to the power source. As a result, the motor simulator can achieve power saving in comparison with the R-L load that consumes power by resistance.

However, it seems that there are some problems with the conventional load simulator. Firstly, a large transformer of grid frequency is required to avoid a circulation current between the load simulator and the test inverter. Secondly, a regenerative converter is also required. Thirdly, the transient responses of the motor are not simulated, because the motor model in the simulator is considered at only steady state.

This paper proposes a suppression method of the circulation current using a common mode transformer in the motor simulator. In the proposed system, the high frequency components of the circulation current are suppressed by a common mode transformer, and the low frequency components of that are suppressed by zero phase current control. In the proposed system, the DC part of the motor simulator can connect to a DC part of the test inverter directly without any convertor. As a result, the proposed system achieves a reduction in size and cost, because a small size medium frequency common mode transformer is used instead of a regenerative converter and grid frequency transformer. In addition, the proposed system can simulate the transient condition of the motor by setting the differential equation into the motor simulator controller and using high speed response controller.

In this paper, at first, the conventional motor simulator and its circulation current problems are introduced. Next, the proposed configuration and principle of the circulation current suppression using common mode transformer is described. At last, the validity of the proposed method is indicated based on the simulation and experimental results.

II. MOTOR SIMULATOR CONSTRUCTION

A. Outline of the motor simulator

Fig. 1 shows the block diagram for the motor simulator. The PWM rectifier is used instead of the load machine. At first, the output voltage of the test inverter is detected. The current command of the PWM rectifier is calculated by the differential equation of the simulated load. When the system simulates an induction motor, the current command of the PWM rectifier is given by motor model equation of the induction motor. Then, the load torque command T_L^* is inputted to the motor model. The primary side current commands i_{d1}^* and i_{q1}^* are then obtained by solving motor model equation in the controller. Finally, the input current of the PWM rectifier, i.e. the output current of the test inverter, is controlled by an auto current regulator in the PWM rectifier based on the current commands i_{d1}^* and i_{q1}^*.

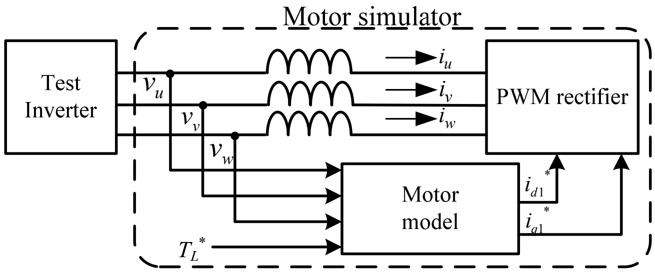


Fig. 1 .Outline of the control method for the motor simulator.

B. Circulation current problem

Fig. 2 shows the circuit configuration of the conventional motor simulator using a PWM rectifier. The motor simulator consists of input reactors, a PWM rectifier, a regenerative converter, and a grid interconnection transformer. The power rating of the regenerative converter and interconnection transformer are required as the same as the PWM rectifier.

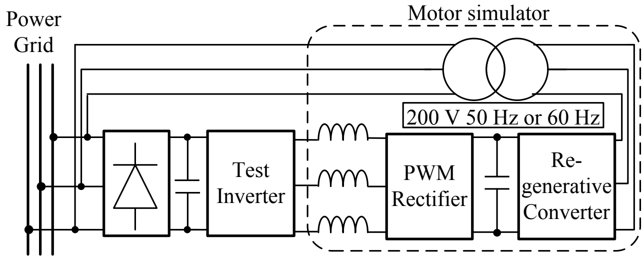
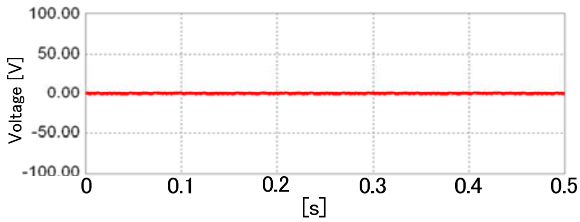


Fig. 2. Inverter test system with a conventional motor simulator.

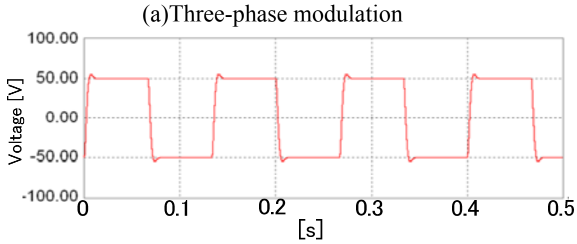
The regenerative converter and interconnection transformer are used from the viewpoint of power saving.

The interconnection transformer is placed in the simulator in order to avoid circulation current between the test inverter and the PWM rectifier. The circulation current is generated by the voltage difference of the zero-phase component between the PWM rectifier and the test inverter. The zero-phase voltage depends on the modulation method of the test inverter.

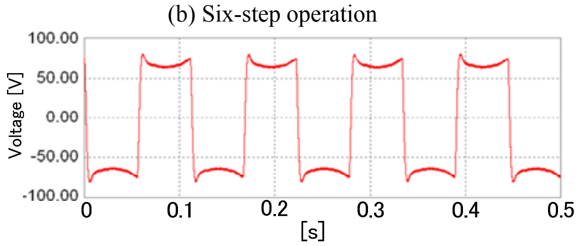
Fig.3 shows the simulation result of the voltage difference of the zero-phase component between the PWM rectifier and the test inverter which is modulated by three-phase modulation, six-step operation and two-phase modulation. The simulation conditions are; the DC voltage is 283V, the output frequency is 25Hz. The voltage waveform does not include switching frequency components to confirm the waveform around fundamental frequency. When the test inverter uses the three-phase modulation, the voltage difference of common mode voltage does not occur. However, when six-step operation and two-phase modulation are applied, the voltage difference of over 50V is generated. Therefore, if the interconnection transformer is not used, then large circulation current flows in system because the zero phase impedance of the system is extremely small.



(a)Three-phase modulation



(b) Six-step operation



(c) Two-phase modulation

Fig.3. the simulation result of the voltage difference of the zero-phase component between the PWM rectifier and the test inverter.

The interconnection transformer of the power grid frequency and the regenerative converter of the same circuit configuration to the PWM rectifier result in the large volume and high cost of the motor simulator. It should be noted that the regenerative converter can be deleted by putting the interconnection transformer on the input side of the motor simulator. However, the motor simulator can not accept the low frequency operation of the test inverter. It means that the system does not simulate start operation of the motor.

III. PROPOSED MOTOR SIMULATOR

A. System configuration

Fig. 4 shows the proposed motor simulator system with a common mode transformer instead of the interconnection transformer and regenerative converter. In the proposed system, the regenerative power is returned to the DC stage of the test inverter. The common mode transformer suppresses the fluctuation of the zero-phase voltage between the test inverter and the PWM rectifier.

Fig.5 shows the principle of the circulation current suppression using common mode transformer. For the circulation current, the common mode transformer becomes high impedance because back electromotive voltage of the transformer is generated at the same direction as shown in Fig.5(a). The regenerative current flows as the normal mode current, then the because back electromotive voltage is generated opposite direction as shown in Fig.5(b).

The zero-phase current of the test inverter has a large fluctuation when two-phase modulation, third harmonic injection modulation, or six-step operation is applied to the test inverter. In those cases, the zero-phase sequence component of the output voltage of the test inverter has three times the frequency component of the output frequency. In particular, the low frequency component appears in the zero-phase sequence voltage when the low speed condition of the motor is simulated. As a result, the size of the common mode transformer becomes large, depending on the low frequency components in the zero-phase sequence voltage.

In order to achieve the size reduction of the common mode transformer, the low frequency component of the zero-phase sequence voltage is suppressed using current control of the PWM rectifier. Therefore, only the switching frequency component of the zero-phase sequence voltage is suppressed by the common mode transformer. Therefore, a small size common mode transformer can be used.

B. Control strategy

Fig. 6 shows the control block diagram for zero current suppression of the low frequency component. The zero-phase current is detected from each of the line currents. The zero-phase current is controlled to zero using an auto current regulator with a PI controller. The output signal of the PI controller is added to each voltage command in the PWM rectifier as the zero-phase voltage command.

Fig.7 shows the control block diagram of proposed motor simulator system. For example, if the motor simulator is used as an induction motor, then the current command of the PWM rectifier is obtained by differential equations on a d-q rotating frame as shown in Eqs. (1), (2) and (3).

$$P\begin{bmatrix} i_{1d} \\ i_{1q} \\ i_{2d} \\ i_{2q} \end{bmatrix} = \begin{bmatrix} -R_1L_2 & \omega_{re}M^2 & R_2M & \omega_{re}L_2M \\ -\omega_{re}M^2 & -R_1L_2 & -\omega_{re}L_2M & R_2M \\ R_1M & -\omega_{re}L_1M & -R_2L_1 & -\omega_{re}L_1L_2 \\ \omega_{re}L_1M & R_1M & \omega_{re}L_1L_2 & -R_2L_1 \end{bmatrix}\begin{bmatrix} i_{1d} \\ i_{1q} \\ i_{2d} \\ i_{2q} \end{bmatrix} + \frac{1}{\sigma}\begin{bmatrix} L_2v_{1d} \\ L_2v_{1q} \\ -Mv_{d1} \\ -Mv_{q1} \end{bmatrix} \quad (1)$$

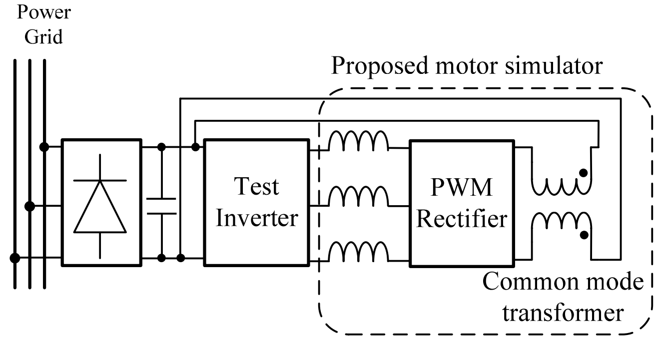
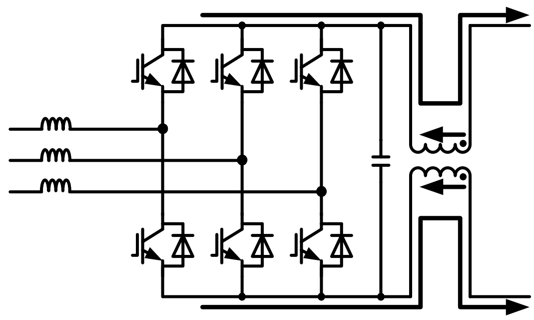


Fig. 4. Inverter test system with the proposed motor simulator using a power converter with a common mode transformer.


(a)Circulation current(common mode)

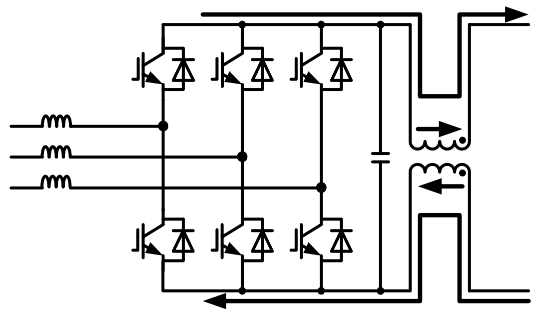

(b)Regenerative current (normal mode)

Fig.5. High frequency component suppression of the circulation current by the Common mode transformer.

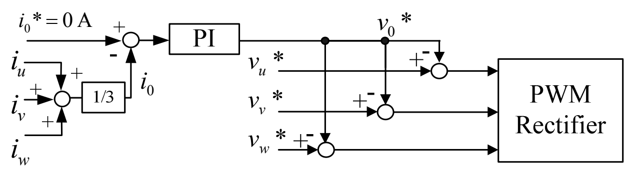


Fig. 6. Low frequency component suppression control of the circulation current for the proposed motor simulator.

$$T = pM(i_{1q}i_{2d} - i_{1d}i_{2q}) \quad (2)$$

$$P\omega_{re} = \frac{1}{J}(T - T_L) \quad (3)$$

where the subscripts 1, 2, d and q are the primary and secondary sides and the d-axis and q-axis components, respectively, *i* is the current, *v* is the voltage, *R* is the resistance, *L* is the leakage inductance, *M* is the inductance, ω_{re} is the

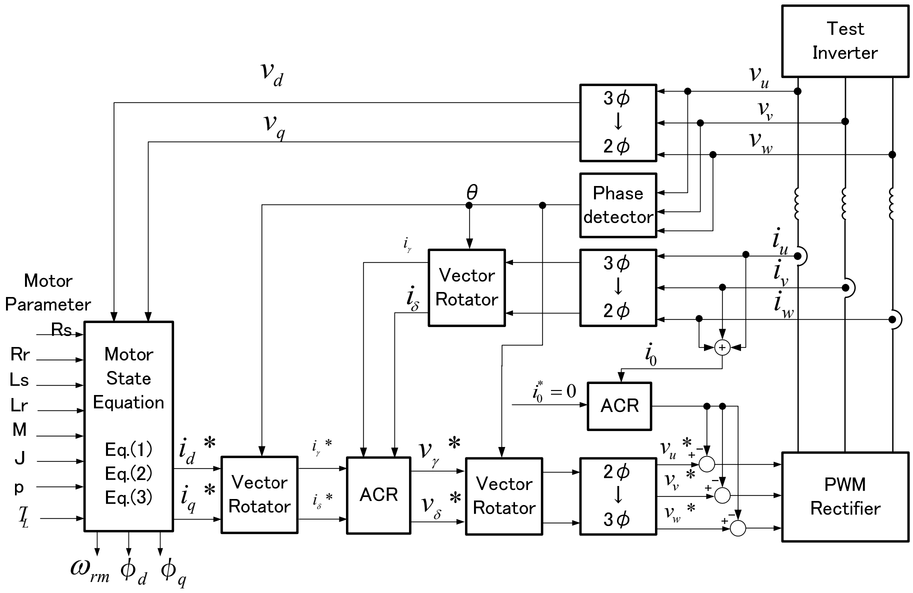


Fig.7. Block diagram of control system.

angular frequency, p is the number of pair poles, $P=d/dt$, T is the output torque, T_L is the load torque, J is the moment of motor inertia, and $\sigma=1-M^2/L_1L_2$. The current command is converted from the d-q components to three-phase components. The primary side current commands i_{d1}^* and i_{q1}^* are then obtained by solving Eqs. (1), (2) and (3) using the Runge-Kutta method [8].

It should be noted that the motor model includes transient terms; the current regulator in the PWM rectifier is designed for very high speed response. Therefore, the proposed system can simulate not only the steady state, but also the transient state of the load.

IV. SIMULSTION AND EXPERIMENTAL RESULTS

To demonstrate the validity of the proposed system, the simulation was implemented. Table 1 shows the simulated motor parameters of a general purpose induction motor of 1.5 kW. The common mode transformer was designed as ideal condition in simulation.

Fig.8 shows the step load response simulation result. The motor is operated at 150r/min (10Hz), and given the load torque 8Nm as of 0.05s. The two-phase modulation is applied as the modulation method of the test inverter. The starter current of the motor simulator agrees well with that of the actual motor in spite of the transient state. The current distortion in Fig. 8 is generated by the load transient and little delay of the current regulator.

Fig.9 shows the voltage difference of the zero-phase voltage between the test inverter and the PWM rectifier. The simulation condition is the same as Fig. 8. In the two-phase modulation, the zero-phase voltage of the test inverter is changed as square. However, the voltage difference converges to zero immediately after the zero-phase voltage is changed.

Fig.10 shows the comparison of the harmonic components of the voltage difference of the common mode transformer terminal between with or without the zero-phase control of the motor simulator. The low frequency component of terminal voltage is decreased from 45V to 3.8V by the zero-phase current control. These results indicate that the common mode transfer can be designed based on the switching frequency of the motor simulator.

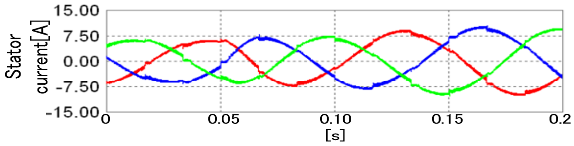
Experimental equipment was constructed to confirm the validity of the proposed motor simulator. The general purpose induction motor, which is the same as that of the simulation, is simulated. A 3 kVA PWM rectifier with a carrier frequency of 10 kHz was used. The output voltage, frequency and carrier

Table1. Simulated motor parameters

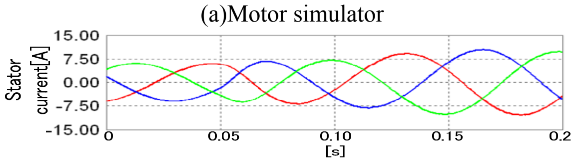
Motor type	Induction motor
Rated power	1.5kW
Rated speed	1420 r/min
Primary winding resistance	1.24 Ω
Secondarily winding resistance	1.01 Ω
Primary leakage inductance	3.53 mH
Secondarily leakage inductance	3.31 mH
Exciting inductance	118.4 mH
Number of poles	4
Rotor moment of inertia	0.0090 kgm2

Table2. Common mode transformer parameters.

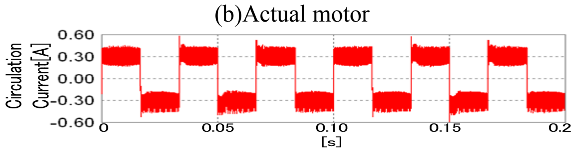
Primary winding resistance	60.7 mΩ
Secondarily winding resistance	71.5 mΩ
Primary leakage inductance	3.13 μH
Secondarily leakage inductance	3.52 μH
Exciting inductance	3.54 mH
Number of turns	31



(a)Motor simulator



(b)Actual motor



(c)Circulation current

Fig.8. Load step response simulation.

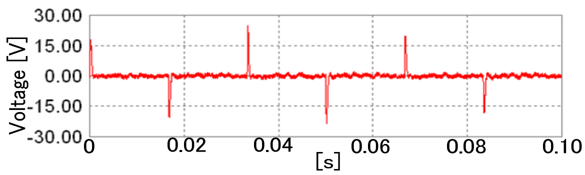
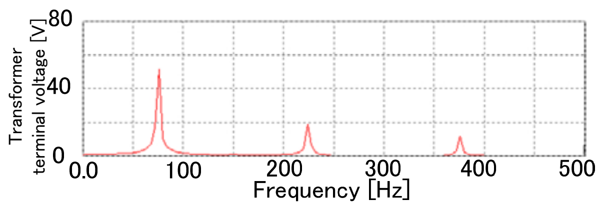
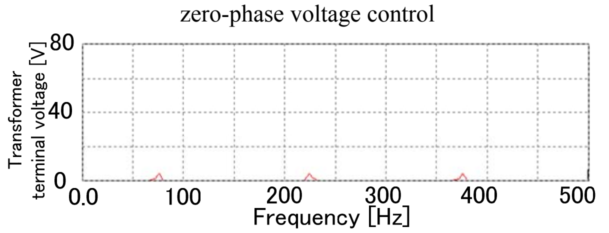


Fig.9. Voltage difference of the zero –phase voltage



(a)Harmonic components of the voltage difference without the zero-phase voltage control



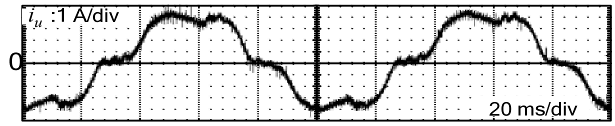
(b)Harmonic components of the voltage difference with the zero-phase voltage control.

Fig.10. Harmonic voltage analysis of transformer terminal.

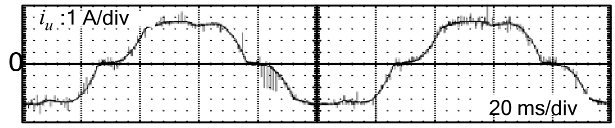
frequency of the test inverter are 40 V, 10 Hz, and 16 kHz, respectively. In addition, third harmonic injection modulation is used. The dead time of the test inverter is set to 3 μs without dead time error compensation. To compare the current waveforms, an actual induction motor with the same specifications as the simulator was used

It is noted that the common mode transformer is described in table 2.The parameters of the common mode transformer are decide by the voltage fluctuation of the zero-phase voltage and switching frequency of the motor simulator.

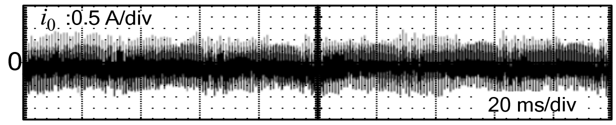
Fig. 11 shows a comparison of the primary current waveform between the motor simulator and the actual motor. The primary current contains a large distortion due to the voltage error caused



(a) Motor simulator

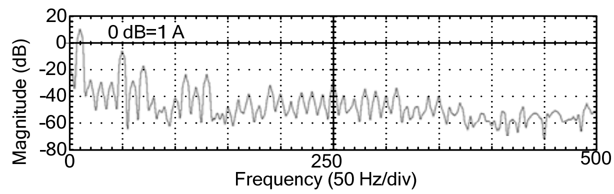


(b) Actual motor

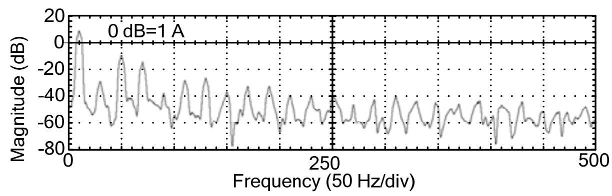


(c) Circulation current

Fig. 11. Comparison of the primary current waveforms.



(a) Motor simulator



(b) Actual motor

Fig. 12. Harmonic primary current analysis.

by the dead time. The motor simulator current waveform agrees well with that of the actual motor, including the distortion. Fig. 11(c) shows the circulation current, i.e. the zero- phase current, of the proposed system. The circulation current is suppressed to less than 0.1 A.

Fig. 12 shows a comparison of the primary current harmonic analysis results. The low frequency components of the motor simulator are in accordance with that of the actual motor. In particular, almost the same values of the fundamental frequency, the fifth and the seventh frequency components are obtained. It should be noted that the simulation range for the high frequency area is limited by the response of the current control loop of the PWM rectifier.

Fig. 13 shows the circulation current harmonic analysis results. The low frequency component of the circulation current is suppressed to around 1% of the fundamental frequency component.

Fig. 14 shows the harmonic analysis results for the terminal voltage of the common mode transformer. The low frequency component is decreased to 1/20 of the high frequency component. Therefore, the small size common mode transformer in the proposed system can be used.

Fig.15 shows the comparison of the primary current waveform between the motor simulator and the actual motor by the simulation at the load torque of 8 Nm(rated torque), output frequency of 50Hz and output voltage of 170V. Note that the simulation result was used because the actual motor has no load machine.

Under the rated torque load condition, the primary current waveform of the motor simulator corresponds to the actual motor exactly. The fundamental current comment value error is 0.04A (2% of the peak current). The circulation current can be suppressed to less than 0.5 $A_{p\text{-}p}$. Note that the circulation current can be decreased by improvement of current response for the zero phase current control.

V. CONCLUSIONS

A motor simulator with a PWM rectifier was presented. Suppression of the circulation current was achieved using a common mode transformer for the high frequency component and zero-phase current control for the low frequency component. The proposed method was experimentally verified, and the following conclusions were reached:

-The proposed system can simulate the motor behavior, including the transient state, for example current distortion by the dead time error of the test inverter.

-The low frequency component of the circulation current was suppressed to 1% of the fundamental component using the proposed method.

-A motor simulator can be constructed using the proposed method, without the requirement for an isolation transformer and regenerative converter.

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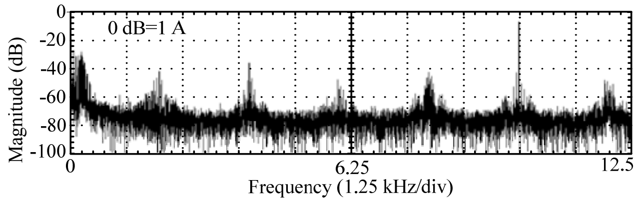
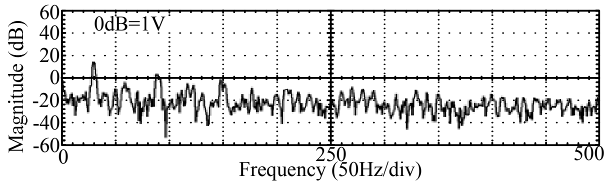
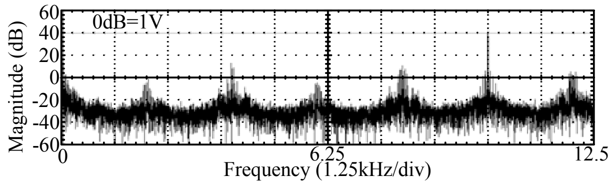


Fig. 13. Harmonic circulating current analysis.

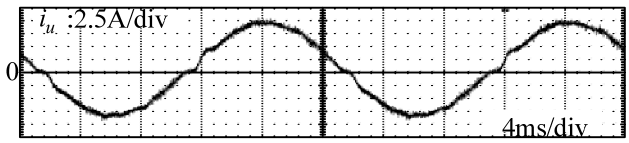


(a) 0-500 Hz

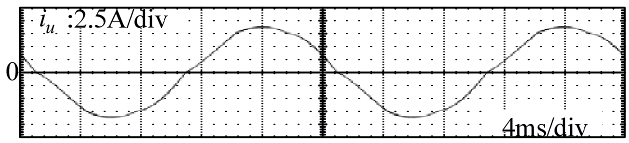


(b) 0-12.5 kHz

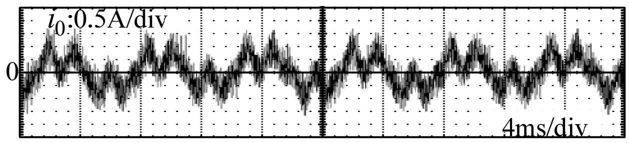
Fig. 14. Harmonic analysis results of the transformer terminal voltage.



(a) Motor simulator



(b) Actual motor



(c) Circulation current

Fig. 15. Comparison of the primary current waveforms (50Hz)