Current and Torque Performance of Induction Motor with Voltage Unbalance Compensator with Voltage Booster

Tomoya Katsuki*, Akihiro Imakiire**, and Satoshi Matsumoto**
*Graduate School of Engineering, **Department of Electrical and Electronic Engineering,
Kyushu Institute of Technology, Kitakyushu, Fukuoka, Japan

***Abstract*—This paper shows the current and torque performance of a 750 W induction motor with a voltage unbalance compensator (VUC) when a DC link voltage is boosted using simulation. The VUC consists of a diode bridge, an inverter, and a voltage booster, however, DC voltage source was used in the simulation simply instead of the diode bridge and voltage booster. The VUC is connected to both of the power grid lines and the induction motor windings. It supplies compensating voltage and keep the terminal voltage balanced of the induction motor when the voltage unbalances occur on the power grid. It was cleared that the compensable range was expanded by boosting the DC link voltage of the VUC in the simulation. Besides, pulsation torque was also suppressed by voltage compensation enhancement. The current and torque waveforms were compered under three conditions such as without the VUC, with the VUC without boosted voltage, and with the VUC with boosted voltage. As a result, it was evidenced the current and torque performance of the induction motor with the VUC is improved by the voltage booster even if the voltage unbalances factor increases.**

***Index Terms*— induction motor, voltage unbalance, voltage unbalance compensation, voltage booster**

I. INTRODUCTION

An induction motors still occupy a major position in the motor market especially in power system applications because it continues to be robust and inexpensive. In addition, it can be easily driven without inverter. Therefore, induction motors are often driven by being directly connected to the three-phase power grid. Its main uses are for fans, blowers, and pumps but also in various applications for heavy industry in factories or power plants.

However, the voltage unbalances in three-phase voltage causes over-currents, local heating, pulsation torque, vibration, and noises for the induction motor. In particular, the effect of overheating due to overcurrent is still serious problem and causes fatal failure such as insulation breakdown of the stator windings [1].

Conventionally, STATCOM (STATic synchronous COMpensator) has been used to solve the unbalanced voltage in power grid to compensate the voltage balanced collectively. The voltage of the distribution line is adjusted by using the voltage generated by flowing the reactive power. However, since such a device is directly connected to the high-voltage power system, it generally requires large-rated capacity and a high-voltage, a large-capacity device of 6.6 kV, MW class. Therefore, the size and cost are problems to introduce the system due to the collectively compensation voltage system. For downsizing, research on making transformer-less has been conducted [2].

An open winding squirrel-cage induction motor combined with an inverter has been proposed to improve power factor in heavy industry [3]-[4]. However, there has been little research into voltage unbalance compensation.

Authors have investigated the induction motor with a voltage unbalance compensator (VUC) to keep drive performance stable by the induction motor itself even when the voltage unbalance occurs.

The induction motor with the VUC is an open-winding squirrel-cage induction motor including the inverter to compensate the unbalance voltage. The VUC consists of a converter, and an inverter. When the voltage unbalances occur in the power grid, the VUC outputs a differential voltage between ideal line voltage and detected line voltage to sustain the terminal voltage balanced. As a result, the motor current can be kept balanced. The VUC is significantly smaller than the conventional STATCOM due to the individually voltage compensation system and can be built into the motor [5].

Assuming that the DC link voltage is given by the average voltage obtained by rectifying the three-phase AC voltage, the DC link voltage decreases due to the occurrence of large voltage unbalance. Then, the maximum voltage that the inverter can output would decrease. If the unbalance is extremely large, the inverter cannot output the voltage required for the voltage unbalance compensation, and the short of voltage compensation remains in the motor current. To solve this problem, we studied a method of increasing the VUC compensation range by voltage booster for the induction motor with the VUC.

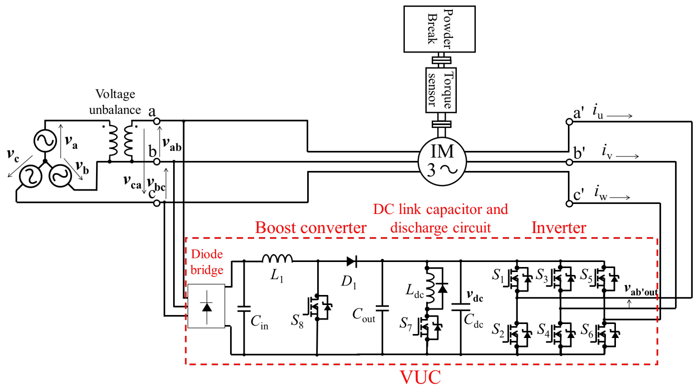
II. SIMULATION

A. Circuit Configuration

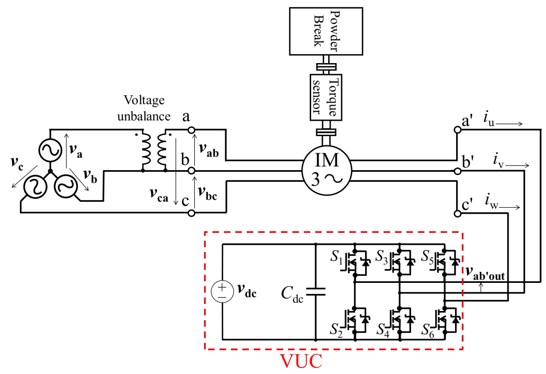
Fig. 1. shows the configuration of the simulation circuit.

Fig. 1. (a) is circuit configuration of the induction motor with VUC using voltage booster. The VUC consist

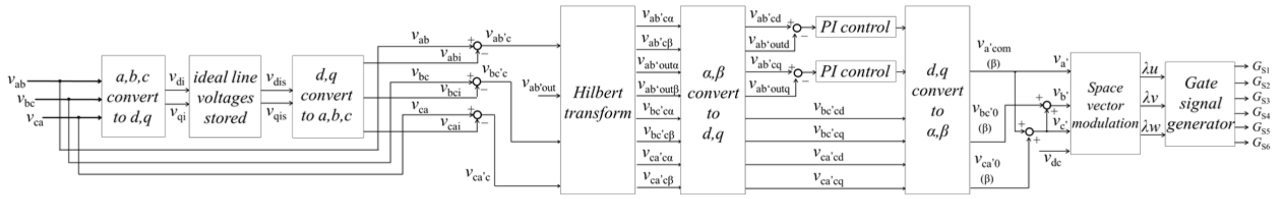
This work was supported by JSPS KAKENHI Grant Number 19K14965.



(a) Circuit with voltage booster.



(b) Simulation circuit



(c) Control circuit of the VUC

Fig. 1. Configuration of the simulation circuit.

of an AC-DC converter, a boost converter, a DC link capacitor and its discharge circuit, and an inverter. The DC link voltage is supplied from power grid line throughout the rectifier. By using the boost converter, it is possible to supply enough DC link voltage to output the voltage required for compensation even when the voltage unbalance occur.

To simplify, the DC voltage source was used instead of voltage booster and AC-DC converter. The boosting of the DC voltage is imitated by raising the output value of the DC voltage source. The voltage unbalance is imitated by inserting a single-phase transformer to grid and the unbalance only occur in the amplitude of the gridline voltage v_{ab}.

Compensating voltage is calculated from the difference between the grid line voltage and ideal line voltage stored during the period when the voltage is balanced. The command output voltage of *a*-phase voltage v_{a}' is obtained from the result of PI control, and the values for the other phases command output voltages are calculated from the relationship between the line voltage and the phase voltage.

B. Simulation Conditions

Table I and Table II shows the motor parameters and simulation conditions.

The induction motor was driven at rated power (750 W). As the load, a constant torque load was used in the simulation assuming the use of the powder brake in the experiment.

The maximum motor current (RMS value) was measured when the voltage unbalance factor (VUF) was increased. The VUF was changed by adjusting the turns ratio of the single-phase transformer inserted between *a*-

TABLE I
MOTOR PARAMETERS

Parameters		Values
Rated power P_{out}	[kW]	0.75
Rated voltage V_a	[V]	200
Rated current I_a	[A]	3.3
Pole Numbers	-	4
Rated frequency f_e	[Hz]	60
Stator Resistance	[Ω]	2.0
Rotor Resistance	[Ω]	1.7
Magnetize Inductance	[H]	0.2
Stator Leakage Inductance	[mH]	8.4
Rotor Leakage Inductance	[mH]	8.4

TABLE II
SIMULATION CONDITIONS

Parameters	Values
Analysis total time	1 s
Time step	250 ns
Frequency of input voltage	60 Hz
DC Link Capacitor	1880 μF
Induction motor	0.75 kW
Switching frequency of inverter	20 kHz
Sampling Period	50 μs
Balanced Line Voltage (RMS Value)	200 V
Period of the VUC running	0.2 s to 1 s
Period of rated operation of the induction motor	0.4 s to 1s
Period of voltage unbalanced	0.75 s to 1s

phase and *b*-phase. The definition of the VUF is based on NEMA. Simulations were performed for three conditions: (a) without the VUC, (b) with the VUC with the voltage booster, and (c) with the VUC with the voltage booster. In addition, the current and torque waveform were compared between (a), (b) and (c).

III. Simulation Results

Fig. 2. shows the %motor current (maximum motor current divided by rated motor current) as a function of the voltage unbalance factor. It expresses the relation between the voltage unbalance factor (VUF) and the maximum RMS value of the motor current.

When the induction motor is driven by connecting to the grid directly without the VUC, the maximum value of the motor current increases significantly according to VUF increases. When the VUF is 10%, the motor current exceeds 140% of the rated current. Further, it reaches 200% of the rated current when the VUF is 20%. In contrast, the induction motor with VUC could motor current balanced at the same values as when the voltage is balanced while the voltage unbalance occurs. However, due to a short of the DC link voltage, the inverter cannot outputs required voltage to compensate the voltage unbalance and the current begins to increase when the VUF exceeds 60%.

On the other hand, when the DC link voltage is boosted 1.2 times of input voltage, the compensation range in which the current can be kept balanced was expanded to around 70% VUF.

When the DC link voltage is further boosted to 1.6 times of input voltage, the inverter could output the required compensation voltage without voltage drop, as a result, the graph is flat over the until 100% VUF range.

Fig. 3. shows the comparison of current waveforms when VUF is 70%.

In Fig. 3(a) without VUC, the maximum motor current is 13.5 A (RMS value), which is more than 4 times the rated value. Then the current unbalance factor (CUF) of the motor currents, calculated according to NEMA standards, was 65.6%. In addition, the phase sequence of the current (*u* and *v*) was reversed.

In Fig. 3(b) with VUC without voltage booster, the motor current values were suppressed to around 1.1 times the rated current. However, due to the short of DC link voltage, the inverter could not output the voltage required for compensation, and distortion and unbalance occurs in the motor current waveform. The CUF of the motor current was 19.1%.

In Fig. 3(c) when the DC link voltage was boosted to 1.6 times of input voltage (=304.9 V), the inverter could output the required voltage even when the VUF was 70%. The motor currents were almost balanced and the distortion had disappeared. The largest current was 102% of the rated current, and the CUF was 2.2 %.

From the results, the induction motor with the VUC with voltage booster could expand the compensable range from 60% to 100% VUF. The CUF could be reduced by 16.9 points compared with the VUC without voltage

Fig. 4. shows a comparison of torque waveforms when the VUF is 70 %.

In Fig. 4(a), the torque ripple rate was 125.5 % (= torque ripple / rated torque ×100). Contrarily, in Fig. 4(b), the VUC enable the pulsation torque to suppress. However, there remains the torque ripple due to short of DC link voltage. The torque ripple was 28.1 %.

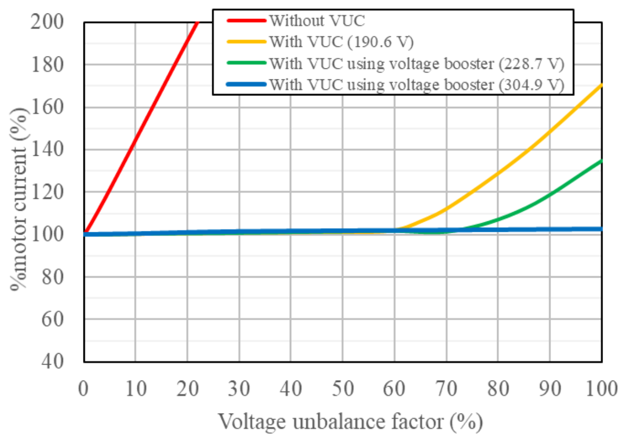
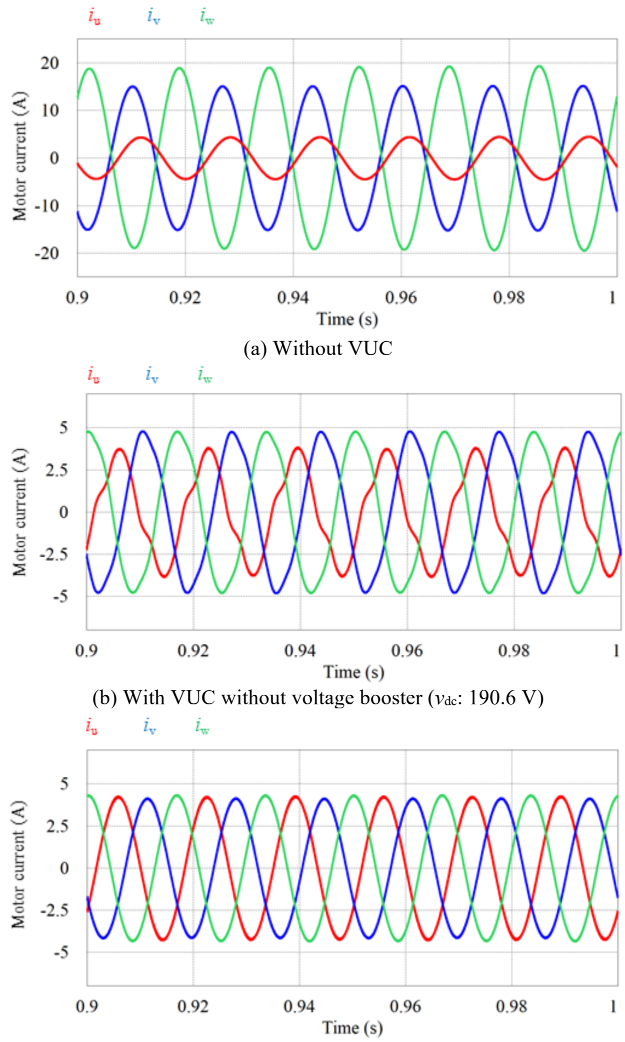


Fig. 2. Relation between VUF and motor current

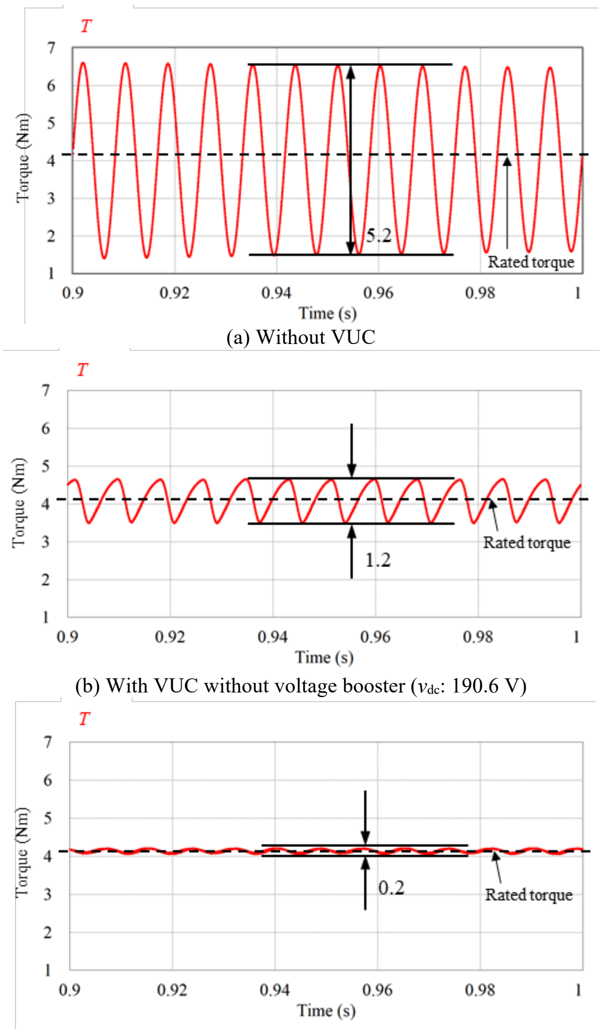


(a) Without VUC

(b) With VUC without voltage booster (v_{dc}: 190.6 V)

(c) With VUC with voltage booster (v_{dc}: 304.9 V)

Fig. 3. Comparison of current waveforms (VUF 70 %).



(a) Without VUC

(b) With VUC without voltage booster (v_{dc}: 190.6 V)

(c) With VUC with voltage booster (v_{dc}: 304.9 V)

Fig. 4. Comparison of torque waveforms (VUF 70 %).

Fig. 4(c) shows the pulsation torque waveforms when the DC link voltage was boosted at 304.9 V, since the motor current unbalance was further improved compared to Fig. 4(b), the torque ripple was also improved and the torque ripple was reduced to 3.7 %.

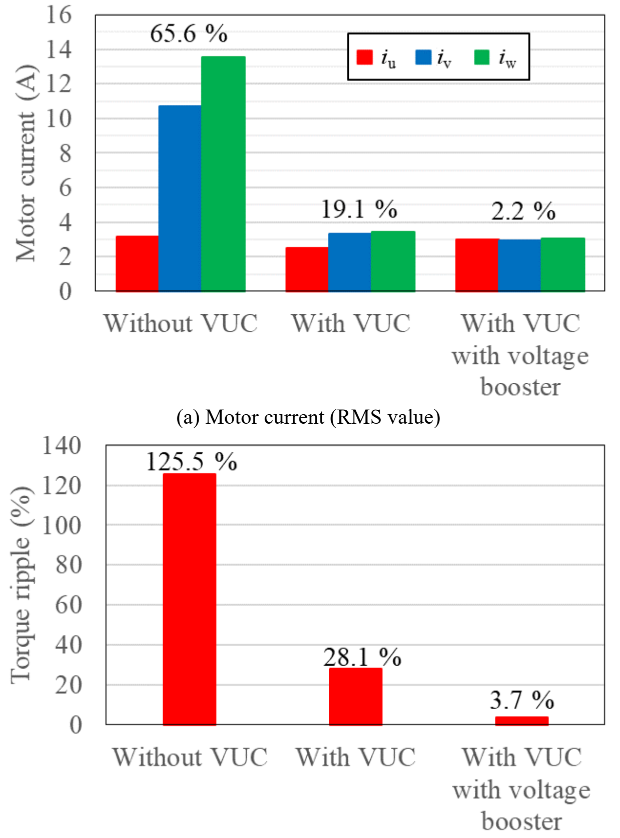
From the results, the induction motor with the VUC with voltage booster could further improve the torque waveform compared with the VUC without voltage booster.

Fig. 5. shows a summary of the simulation results.

IV. Conclusions

This paper discussed the current and torque performance of the 750 W induction motor with the voltage unbalance compensator (VUC) when the DC link voltage was boosted using simulation. The VUC consists of the inverter, the converter, and the voltage booster. It is connected to both of the power grid lines and the induction motor windings. The VUC enables the motor current to maintain balanced and the torque ripple to suppress.

However, when the voltage sag is serious, it cannot compensate for the voltage unbalance because of the



(a) Motor current (RMS value)

(b) Pulsation torque

Fig. 5. Motor current and torque ripple (VUF 70 %).

short of the DC link voltage obtained from the power grid throughout the rectifier. Therefore, the induction motor with the VUC with voltage booster was studied in the paper.

The motor current was unbalanced when the VUF exceeds 60 % even if using the VUC. On the other hand, when the DC link voltage was boosted 1.2 times of input voltage, the compensation range in which the current could be kept balanced was expanded to around 70 % VUF. When the DC link voltage was further boosted to 1.6 times of input voltage, the inverter could output the required compensation voltage without voltage drop. As a result, the VUC with the voltage booster could compensate for the voltage until 100% VUF.

Besides, pulsation torque was also suppressed by voltage compensation enhancement. it was proved the current and torque performance of the induction motor with the VUC is improved by the voltage booster even if the voltage unbalances factor further increases more than 60% VUF.

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number 19K14965. The authors would like to acknowledge the concerned members.

References

[1] P. Pillay and M. Manyage, “Loss of Life in Induction Machines Operating With Unbalanced Supplies,” IEEE

Transactions On Energy Conversion, Vol. 21, No. 4, pp.813-822, December 2006.
[2] H. Akagi, S. Inoue and T. Yoshii, "Control and Performance of a Transformerless Cascade PWM STATCOM With Star Configuration," IEEE Transactions On Industry Applications, Vol. 43, No. 4, pp.1041-1049, July/August 2007.
[3] D. B. Rathnayake, S. G. Abeyratne and T. A. Lipo, "A Dual Purpose Induction Motor Drive for a High Inertia Load with Both Quick Run-Up and Power Factor Correction Capability," 2017 IEEE 3rd International Future Energy Electronics Conference and ECCE Asia (IFEEC 2017 – ECCE Asia), pp.388-393, June 2017.
[4] A. M. Knight, J. C. Salmon, R. Haque, N. Perera, M. S. Toulabi, "A Grid-Connected Induction Machine Capable of Operation at Unity and Leading Power Factor," 2013 IEEE Energy Conversion Congress and Exposition, pp.238-245, September 2013.
[5] A. Imakiire and T. A. Lipo, "Induction Machine with Localized Voltage Unbalance Compensation," 2019 IEEE International Electric Machines & Drives Conference (IEMDC), pp.1248-1255, May 2019.