Multi-level Operation of Triple Two-Level PWM Converters

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***Abstract*—This paper presents a new connection method of triple two-level PWM converters to provide multi-level output waveform to a motor/transformer which has triple independent sets of three-phase winding. By simply changing the connection between the PWM converters and the windings of the motor/transformer, the level of winding voltage can be increased without any hardware modification. With triple 2-level converters, the level of the voltage of a phase winding can be increased up to 9 levels for delta-connected winding and 17 levels for wye-connected winding. The number of the voltage level of the proposed connection method is equivalent to that of 5-level converter. The equivalent circuits for the proposed connection are derived for both delta- and wye-connected winding cases. Through the equivalent circuit, the winding voltage has been expressed in terms of phase voltage of each PWM converter. The validity of the equivalent circuit and the proposed connection has been verified with experimental result.**

Keywords— Multi-winding transformer, open-end winding, parallel converter.

I. Introduction

To achieve multi-MW DC-AC or AC-DC power conversion less than or equal to $690V_{ac,rms}$, multiple converters operate in parallel due to the limited current rating of power semiconductors [1]. Power-conditioning converters for grid supporting battery energy storage system (BESS) and for large-scale solar farms would be examples of this type of configuration. In this configuration, the converters can be operated independently or in synchronized manner for interleaving operation.

In case of battery energy storage system and solar farm, DC sources can easily be separated due to the fact that it is made up of many parallel/series-connected small DC voltage cells. Also, DC sources for wind turbine generators and propulsion motors can be easily separated with multi-pulse transformers in AC side. With isolated DC source, open-end winding structure can be used to improve current waveform [2]~[3]. By connecting two converters to each end of the winding, the winding voltage can have more levels without any zero-sequence circulating current [4].

For multi-MW BESS and solar farms, a transformer is needed to interface with the grid. If the transformer has multiple sets of secondary winding, where PWM converters are connected, the harmonics of the primary-side grid current can be reduced conspicuously through interleaving operation[5]~[6]. Also, high power wind turbine generators and ship propulsion motors usually have multiple independent three-phase windings to accommodate high voltage and high current and to enhance the availability through redundancy [7]~[8]. In these cases, each three-phase winding is connected to three-phase PWM converters. In [9], a new topology is proposed for 3-winding transformer. By changing a configuration of two secondary windings, two converters synthesize one winding voltage like open-end structure while the effect of interleaving remains on the primary-side.

In this paper, a new method to connect triple three-phase windings and triple three-phase PWM converters is proposed. If triple isolated DC sources, triple three-phase windings, and triple 2-level PWM converters are simultaneously available, simple variation of the connection between converters and windings would result in conspicuous reduction of harmonics in converter-side current. Meanwhile, the grid-side current contains very low THD in case of grid-interface and low ripple torque in case of motor drive. An equivalent circuit is derived for the proposed connection. The winding voltage can be expressed in terms of phase voltage of each PWM converter.

II. Triple Three-Phase Winding Systems

The conventional connection method and proposed connection method are compared in Fig. 1 and Fig. 2. Each winding is represented by simple one inductance for explanation. In the figures, the three-phase windings on secondary-side of a multi-winding transformer have been assumed to be delta-connected. However, wye-connection can be used without loss of generality.

In the conventional connection, one three-phase winding is connected to the three-phase output of one converter respectively as shown in Fig. 1. On the other hands, in the proposed connection method, each of one three-phase winding is connected to three different converters as shown in Fig. 2. For example, in case of winding 1, a-phase terminal is connected to a-phase output of the converter 1, b-phase terminal to b-phase output of the converter 2 and c-phase terminal to c-phase output of the converter 3. By connecting in this way, two different phase of two converters are connected each end of one winding. This feature enables triple two-level

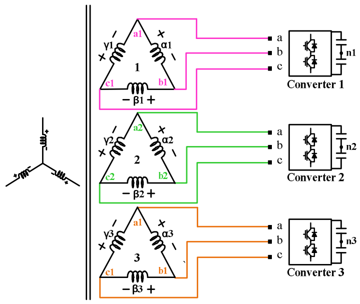

Fig. 1 Conventional connection method between 4-winding transformer and converters

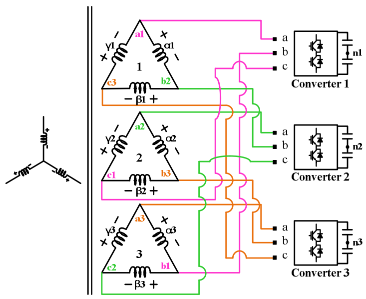

Fig. 2. Proposed connection method between 4-winding transformer and converters

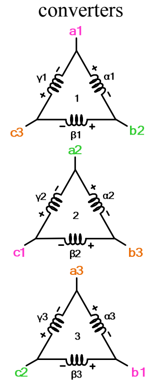

Fig. 3. Circuit diagram with only secondary windings drawn

converters to provide multi-level voltage to each winding like open-ending winding or the topology proposed in [9].

With multi-level voltage, the current through the secondary windings has much reduced harmonics compared to the conventional connection. It should be noted that primary-side current has identical waveform in either case, with reduced harmonics by interleaving. However, in the case of the conventional connection, the interleaving operation gives no benefit to the secondary-winding current in the sense of harmonics and number of levels to each winding. Since the proposed method only changes the connection between the converters and the windings, it can also be applied to wye-connected windings. In this paper, equivalent circuits for both delta- and wye-windings are derived based on the superposition principle.

III. Equivalent circuit for delta-connected winding

To simplify the circuit in Fig. 2, only secondary windings are represented in Fig. 3. The equivalent circuit for each converter

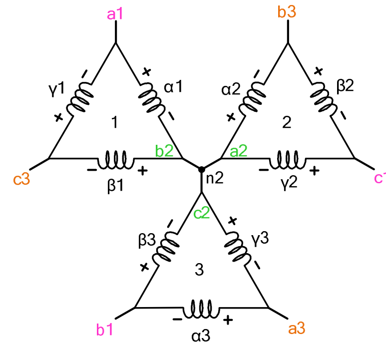

Fig. 4. Equivalent circuit when converter 2 is deactivated

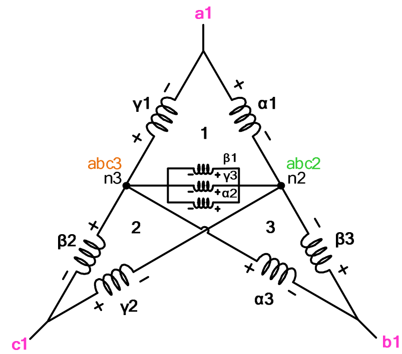

Fig. 5. Equivalent circuit when converter 2,3 are deactivated

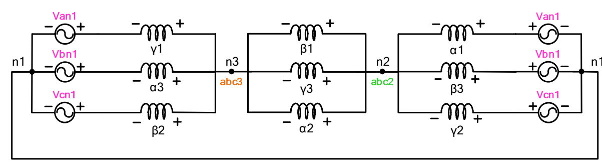

Fig. 6. Simplified equivalent circuit for converter 1 with deactivated converter 2 and converter 3.

can be derived with the superposition principle. To derive the equivalent circuit of the converter based on superposition principle, the voltage sources representing the converter 2, 3 should be deactivated.

In Fig. 4, the three-phase voltage source corresponding to the converter 2 is deactivated. If the voltage source corresponding to the converter 3 is also deactivated, the circuit becomes one in Fig. 5. Node n2 and n3 indicates the neutral point of converter 2 and converter 3, respectively. The equivalent circuit in Fig. 5 can be rearranged as a circuit in Fig. 6 by splitting the voltage source of converter 1 into two identical voltage sources.

The output voltage of PWM converter can be decomposed into balanced three-phase voltage and zero-sequence voltage. The zero-sequence voltage of converter 1 can be denoted by V_{sn1} as (1). And (2) holds for balanced three-phase voltage by converter 1 where instantaneous sum of the phase voltages is always null under the assumption of the balanced load condition.

$$V_{xn1} = V_{xs} + V_{sn1}, x = a, b, c \tag{1}$$

$$V_{as1} + V_{bs1} + V_{cs1} = 0 \tag{2}$$

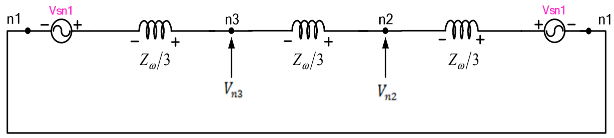

Fig. 7. Equivalent circuit for zero-sequence voltage of converter 1

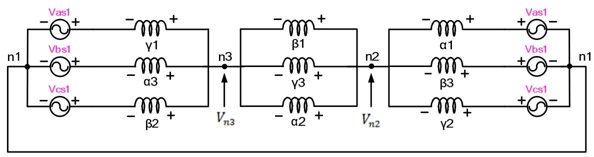

Fig. 8 Equivalent circuit for balanced three-phase voltage of converter 1

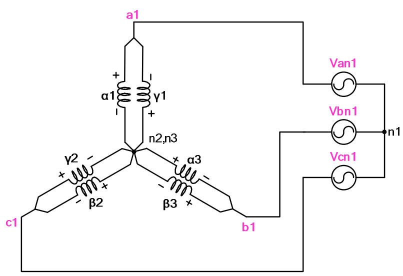

Fig. 9 Equivalent circuit for converter 1 after deactivation of converter 2 and 3 (Delta-connected case)

A. Equivalent circuit for zero-sequence voltage

Since the two star points in Fig. 6 are the same one and the load impedance of windings are assumed to have the same value as Z_ω , the equivalent circuit for the zero-sequence voltage can be described as shown in Fig. 7. It can be easily seen that there is no path for zero-sequence current. Therefore, voltage potential of node n2 and n3 is equal for converter 1 in case of zero-sequence voltage.

B. Equivalent circuit for balanced three-phase voltage

Similarly, the equivalent circuit for balanced three-phase voltage can be derived as shown in Fig. 8. Then, (3) and (4) holds for node n2, n3.

$$\frac{V_{n2}-V_{as1}}{Z_\omega}+\frac{V_{n2}-V_{bs1}}{Z_\omega}+\frac{V_{n2}-V_{cs1}}{Z_\omega}+\frac{V_{n2}-V_{n3}}{Z_\omega/3}=0 \quad (3)$$

$$\frac{V_{n3}-V_{as1}}{Z_\omega}+\frac{V_{n3}-V_{bs1}}{Z_\omega}+\frac{V_{n3}-V_{cs1}}{Z_\omega}+\frac{V_{n3}-V_{n2}}{Z_\omega/3}=0 \quad (4)$$

By substituting (2) into (3),(4), it can be shown that (5) holds for neutral point of converter 2 and 3.

$$V_{n2}=V_{n3} \quad (5)$$

In summary, node n2 and n3 always have the same potential for both balanced three-phase voltage and zero-sequence voltage of converter 1. Therefore, no current flows between these two nodes. The impedance between node n2 and node n3 can be neglected and the equivalent circuit for converter 1 can be simplified further as the circuit in Fig. 9.

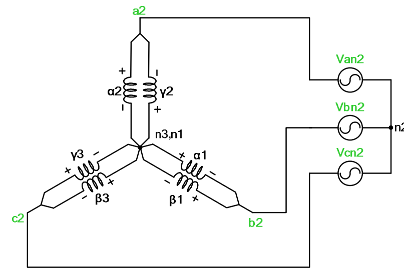

Fig. 10 Equivalent circuit for converter 2 after deactivation of converter 1 and 3(Delta-connected case)

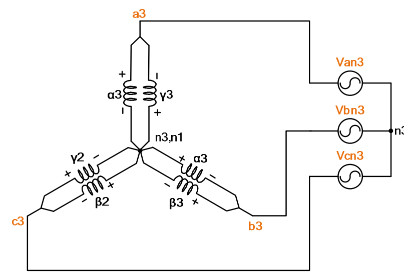

Fig. 11 Equivalent circuit for converter 3 after deactivation of converter 1 and 2 (Delta-connected case)

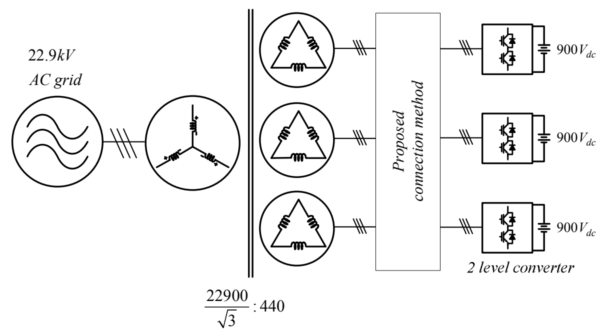

Fig. 12 Circuit diagram of 3MW BESS for simulation

Similarly, the equivalent circuit for converter 2, 3 can be derived as Fig. 10, Fig. 11. Based on these equivalent circuits, the winding voltage can be expressed by output voltage of triple converters as (6).

$$\begin{bmatrix} V_{\alpha 1} \\ V_{\beta 1} \\ V_{\gamma 1} \end{bmatrix} = \begin{bmatrix} V_{as1}-V_{bs2} \\ V_{bs2}-V_{cs3} \\ V_{cs3}-V_{as1} \end{bmatrix}, \begin{bmatrix} V_{\alpha 2} \\ V_{\beta 2} \\ V_{\gamma 2} \end{bmatrix} = \begin{bmatrix} V_{as2}-V_{bs3} \\ V_{bs3}-V_{cs1} \\ V_{cs1}-V_{as2} \end{bmatrix}, \begin{bmatrix} V_{\alpha 3} \\ V_{\beta 3} \\ V_{\gamma 3} \end{bmatrix} = \begin{bmatrix} V_{as3}-V_{bs1} \\ V_{bs1}-V_{cs2} \\ V_{cs2}-V_{as3} \end{bmatrix} \quad (6)$$

The phase-voltage of two different converters synthesize one line to line voltage of three-phase winding in (6). If three 2-level converters are used, the level of the voltage of each winding can be increased up to 9, while the conventional connection can only provide 3 levels.

C. Simulation result

Computer simulation for 3MW BESS is conducted to verify the validity of equivalent circuit. The circuit diagram of the system is shown in Fig. 12. The parameters used for the simulation is shown in Table 1. The waveform of the grid-side

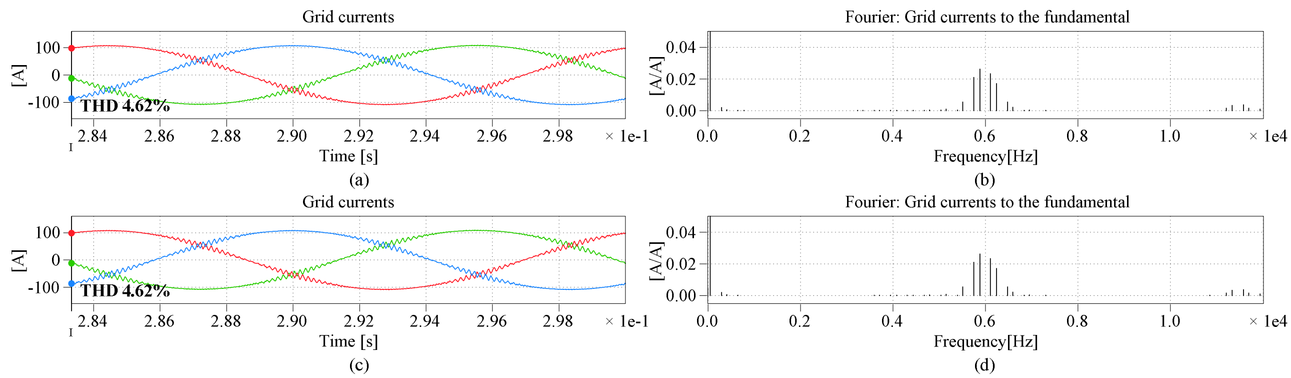

Fig. 13 Grid-side current in case of conventional connection (a) Waveform (b) Frequency spectrum in case of proposed connection (c) Waveform (d) Frequency spectrum

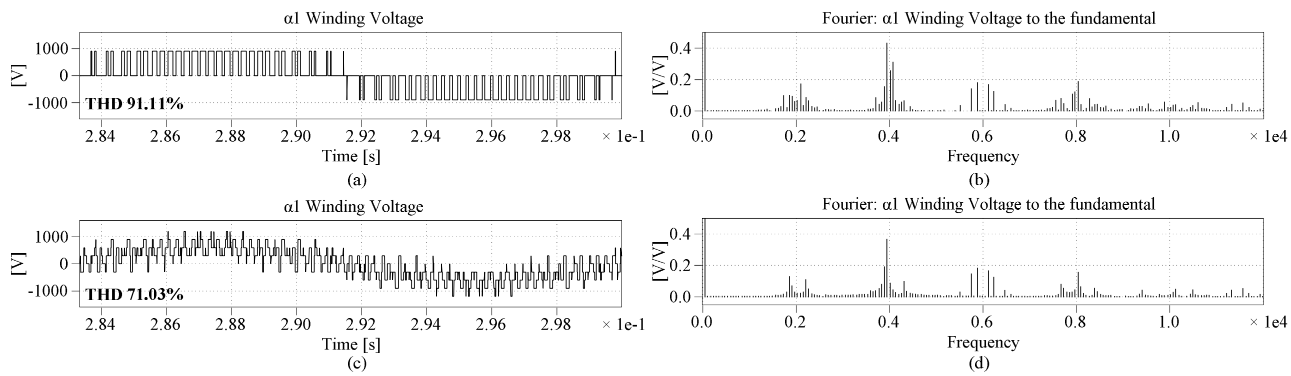

Fig. 14 α1 winding voltage (Delta-connected case) in case of conventional connection (a) Waveform (b) Frequency spectrum, in case of proposed connection (c) Waveform (d) Frequency spectrum

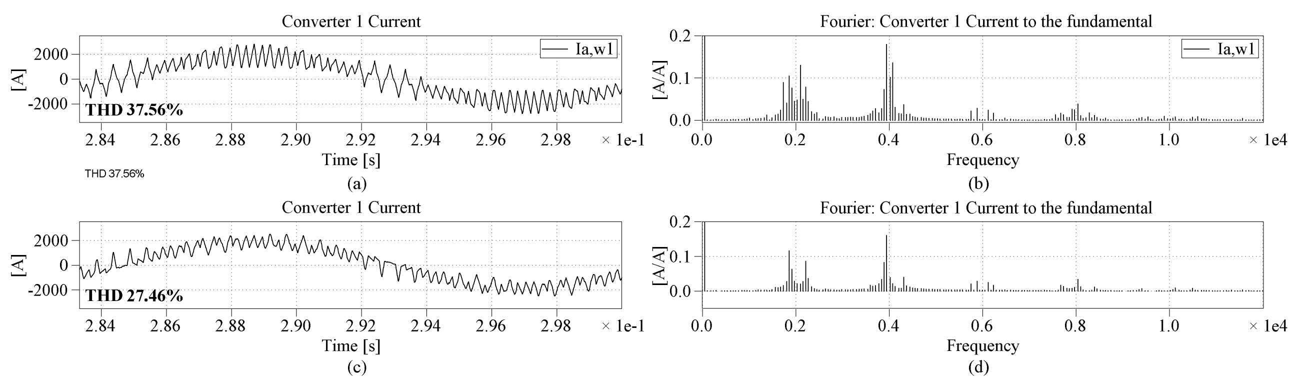

Fig. 15 Converter 1 a-phase current in case of conventional connection (a) Waveform (b) Frequency spectrum in case of proposed connection (c) Waveform (d) Frequency spectrum

current, the voltage of each secondary winding, and the secondary current flowing through the converters are shown in Fig. 13, Fig. 14, and Fig. 15, respectively according to the connection methods.

The grid-side current of both the conventional and proposed connection have the same waveform as Fig. 13. Proposed connection does not have any further benefit on grid-side current as expected. Both waveform of grid-side current has low harmonics with virtue of 120° interleaving between three converters. The winding voltage of conventional connection

TABLE I. PARAMETERS FOR SIMULATION

Item name	Value
DC link (V_{dc})	900 V
Leakage inductance of secondary winding (L_{lk})	0.035 p.u.
Switching frequency (f_{sw})	2.0 kHz
PWM method	SVPWM

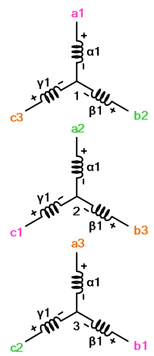

Fig. 16. Circuit diagram with only secondary windings drawn (Wye-connected case)

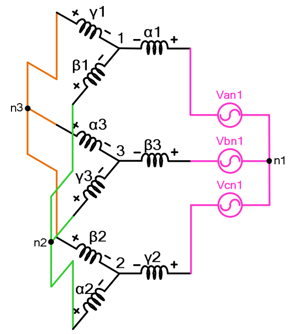

Fig. 17 Equivalent circuit when converter 2,3 are deactivated (Wye-connected case)

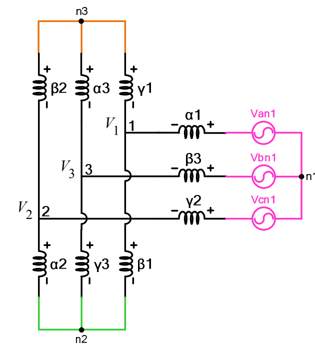

Fig. 18. Simplified equivalent circuit for converter 1. (Wye-connected case)

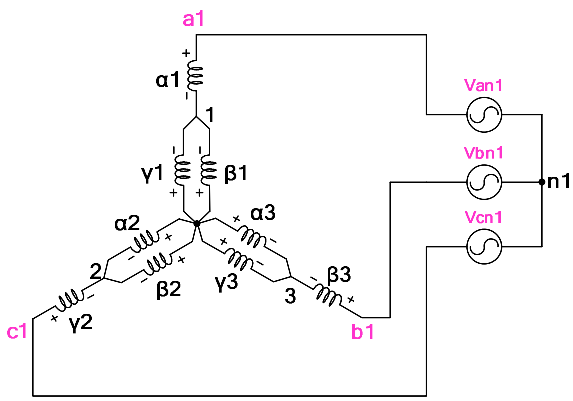

Fig. 19 Equivalent circuit for converter 1

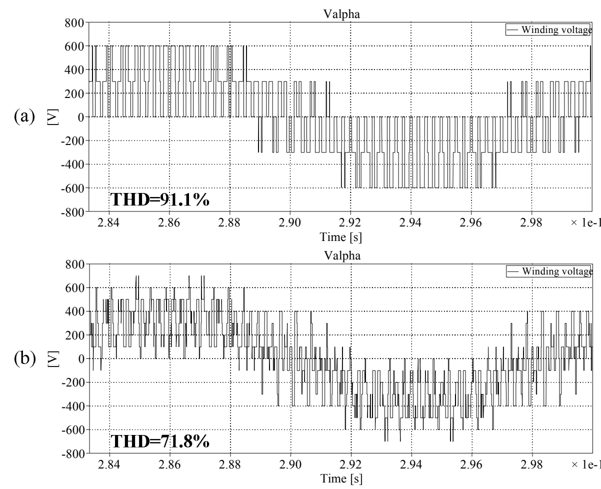

Fig. 20 α1 winding voltage for wye-connected case
(a) Conventional connection (b) Proposed connection

has three levels, while the proposed one has nine levels. THD of winding voltage of the conventional connection is 91% as shown in Fig. 14, whereas that of the proposed connection is 71%. The THD of voltage is reduced by 30% after this simple connection change.

Thanks to the increased number of voltage level, THD of converter-side current is decreased by 28% as shown in Fig. 15(c) and (d). The reduced harmonic means less copper loss in the winding and less switching and conduction loss at the converter itself.

IV. Equivalent Circuit for Wye-Connected Winding

The equivalent circuit for wye-connected winding can be derived through the same procedures. By deactivating voltage sources representing converter 2 and converter 3's from the circuit in Fig. 16, the equivalent circuit for converter 1 can be drawn as in Fig. 17. The circuit in Fig. 17 can be further simplified to the circuit in Fig. 18.

As like the case of delta-connected winding, the node n2 and n3 Fig. 17, Fig. 18 have the same potential for both balanced three-phase voltage and zero-sequence voltage of converter 1 and the sum of current flowing into these two nodes is always zero. Therefore, node n2 and n3 can be though as one single node for converter 1. And, the equivalent circuit in Fig. 18 can be further simplified as a circuit in Fig. 19. The equivalent circuit for other converters can be derived in the same manner. The voltage of winding 1 can be expressed by output of three converters as (7).

$$\begin{bmatrix} V_{\alpha 1} \\ V_{\beta 1} \\ V_{\gamma 1} \end{bmatrix} = \begin{bmatrix} \frac{2}{3}V_{as1} - \frac{1}{3}V_{bs2} - \frac{1}{3}V_{cs3} \\ -\frac{1}{3}V_{as1} + \frac{2}{3}V_{bs2} - \frac{1}{3}V_{cs3} \\ -\frac{1}{3}V_{as1} - \frac{1}{3}V_{bs2} + \frac{2}{3}V_{cs3} \end{bmatrix} \quad (7)$$

The output voltages of three converters are applied in one winding. The level of output phase-voltage of 2-level converter is 5. While the number increases up to 17 according to (7) in the case with the proposed connection.

The transformer with delta-connected secondary windings in Fig. 12 is changed to the one with wye-connected secondary windings to verify the validity of equivalent circuit. The same parameters with the case of delta-winding have been used for the simulation. The waveform of $\alpha 1$ winding is shown in Fig. 20. It is clearly seen that the number of voltage level is 17. Note that, even though the number of voltage level increases,

TABLE II. PARAMETERS OF PMSM WITH TRIPLE THREE-PHASE STATOR WINDINGS.

Item	Value
P_{rated} (Total)	3.9 kW
Pole pair	4
R_s	0.2 Ω
L_m	2.1 mH
L_{lk}	0.17 mH

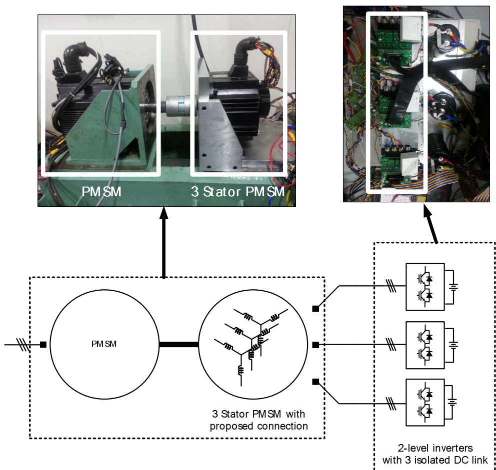

Fig. 25 Experimental setup with 3 stator-winding PMSM

the improvement in THD of winding voltage remains the same as delta-winding case.

V. EXPERIMENTAL RESULT

To demonstrate the applicability of the proposed connection to multi-MW drive system, a reduced scale prototype has been built based on a Permanent Magnet Synchronous Machine (PMSM) with triple three-phase stator-windings. The parameters for the PMSM are shown in Table II. The stator windings are wye-connected. Triple 2-level PWM converters with separate DC source are used to drive the motor. The voltage of each DC link of the converters has been set to 100 V. The carriers for each converter are phase-shifted by 120° with 5 kHz switching frequency to emulate MW class inverter. SVPWM has been used. When the motor is operated in 600 r/min and the reference for q-axis current of each winding is set as 5A, the winding voltage and current is measured to check the effect of proposed connection method.

The line to line voltage waveform is shown in Fig. 21 for and phase voltage in Fig. 22 for phase voltage. With the conventional connection, the line to line voltage has 3 levels. While the number of level increases to 9 with the proposed connection method. For phase voltage, the number of level increases from 5 to 17. With 120° interleaving, THD of winding voltage is decreased by 28%. In the experiment, THD of converter-side current has been reduced by 43% as Fig. 23. The relatively large harmonic currents on both connection cases could be due to the small per unit leakage inductance of

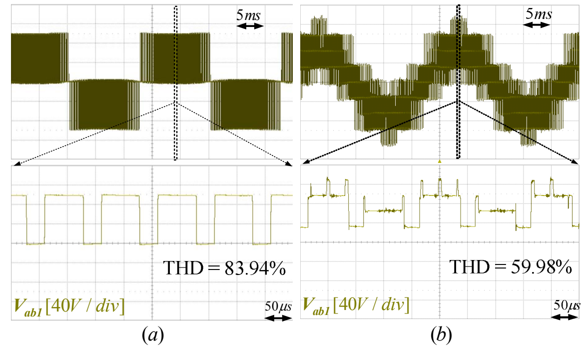

Fig. 21 Line-line voltage of winding 1
(a) Conventional connection (b) Proposed connection

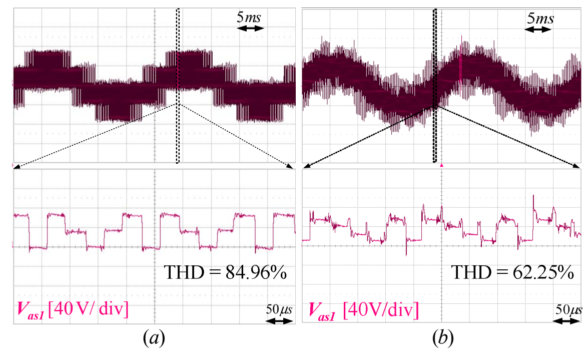

Fig. 22 Phase voltage of winding 1
(a) Conventional connection (b) Proposed connection

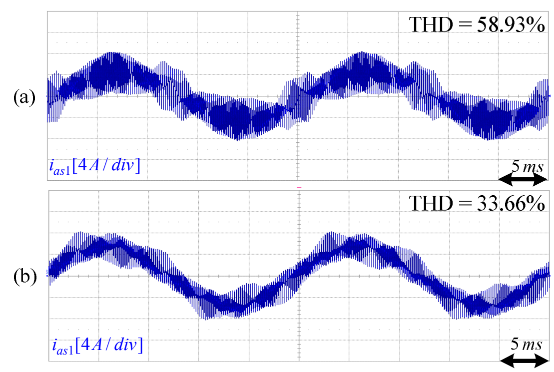

Fig. 23 Converter 1 A-phase current of
(a) Conventional connection (b) Proposed connection

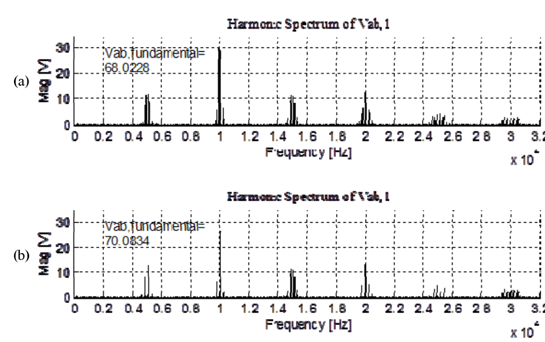

Fig. 24 FFT of line-line voltage
(a) Conventional connection (b) Proposed connection

the PMSM. Contrast to no interleaving operation case, where the harmonic voltage applies to both leakage and mutual inductance of PMSM, the phase-shifted harmonics are only related to the leakage inductance of each windings [10]. The interleaving operation would deteriorate the harmonic suppression on converter-side compared to the drive without interleaving operation[11]. If the same switching frequency with the interleaving operation is applied to multi-MW induction motor drive, the current harmonics with interleaving would be decreased significantly because of the relatively large stator leakage inductance, where the harmonic voltage is applied. From harmonic spectrum of line to line voltage in Fig. 24, it can be seen that around a half of harmonic voltages in f_{sw} , $2f_{sw}$ sideband has been eliminated thanks to the increased voltage level of the proposed connection.

VI. Conclusion

A new connection method for triple three-phase windings and triple PWM converters with triple isolated DC sources has been proposed. By simply changing the connection between the converters and windings, the winding voltage level can be increased up to 9 for delta-connected winding and 17 for wye-connected winding with 2-level PWM converters. The number of voltage level is equivalent to that of the winding connected to 5-level converter. The equivalent circuits for both delta-connected and wye-connected triple three-phase windings are derived. From the equivalent circuits, winding voltage can be represented by the output voltage of triple converters. The validity of the circuit and connection has been confirmed by both computer simulation and experimental results based on small scale PMSM drive system with triple stator-winding set. The THD of converter current is reduced by 43% with the proposed connection in the experiment.

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