Loss comparison of the 3 level topologies for four-leg voltage converters

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Abstract— **This paper is to compare the loss of the each 3 level topologies for four-leg voltage converters. In case of the power conditioning system connected to the grid without a transformer, 4 leg topology is essential to cover the unbalanced three phase loads. Using simulations with real loss data table of the power switches, loss analysis of the each 3 level topology with 4 legs according to the different PWM methods is carried out at the normal state and at the stand-alone operation with various kinds of load conditions. From the simulation and experimental results, it is shown that T-type with the MLPWM is the most efficient combination regardless of whether the loads are balanced or not.**

***Keywords*—4 Leg, Loss, NPC, T-type, CPWM, DPWM, MLDPWM**

I. INTRODUCTION

With concerns to global warming and emissions, the interest in the distributed generation based on the renewable energy has been increasing. Most of the distributed generators based on the renewables have power conditioning system (PCS) to interface variable source with the grid. In case of grid fault, the PCS has to be operated in stand-alone mode providing electric power to the unbalanced three phase load.

There are various types of PCSs. In general, 2 level 3 leg PCS is widely used because of its simple structure and the easiness in control. However the multi-level PCSs are getting attentions owing to the better efficiency and less size of the output filter. Furthermore, less common-mode voltage and dV/dt give additional benefits in the EMI and the leakage current. Among multi-level converters, 3 level Neutral Point Clamped (NPC) topology converter is the most popular one because of long history of application and its relatively simple control. Besides, the T-type topology also belongs to widely used multi-level converter topologies. Recently the T-type topology is remarkably focused on account of the smaller number of power switches and less conduction losses. Also it is well known that the efficiency of the T-type is higher than that of the others in medium switching frequency range (4~20 kHz) among these 3 level 3 leg topologies [1].

In case of the normal state in which the PCS is connected to the grid, the 3 level 3 leg converter does not make any problems whether three phase loads are balanced or not. But in abnormal state when the PCS is disconnected to the grid because of the grid faults, the phase voltages of the each phase in the conventional 3 leg PCS are affected by the unbalanced loads. In the extreme case where only 2 single phase loads are connected between two phases, the phase voltage would not be $V_{l-l}/\sqrt{3}$ but $V_{l-l}/2$. To handle this unbalanced load, 3 leg converters could be operated as three single phase half bridge converters at the cost of reduced output ac voltage. Likewise, a transformer could be applied to the output of PCS at the cost of efficiency, size and weight. With the development of the power semiconductors, the cost to performance ratio has dropped continuously. Thus 4 leg PCS would be a solution to handle these unbalanced three phase loads.

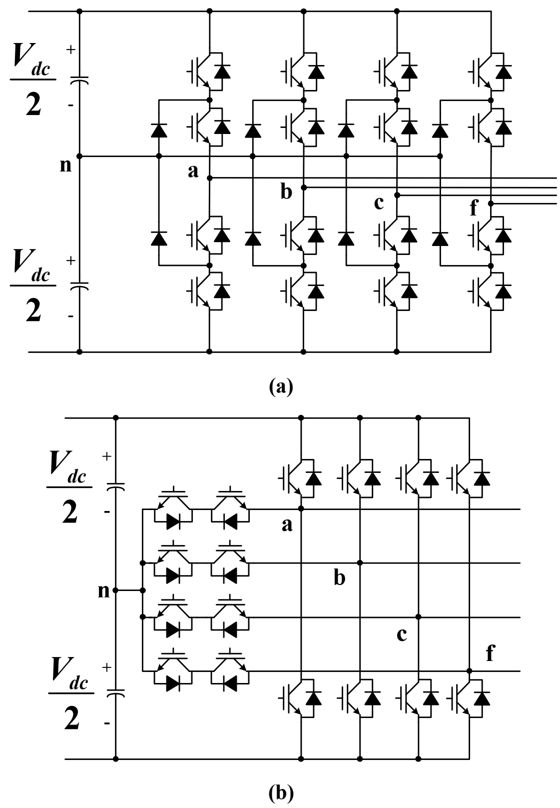


Figure 1. 3 level 4 leg topology (a) NPC, (b) T-type

In this paper, two 3 level 4 leg topologies, namely NPC converter and T-type converter shown in Fig. 1, have been considered for PCS application. Several PWM methods for 3 level 4 leg inverters have been reported in [2]. The losses of NPC and T type converters have been compared in the case of 3 leg inverter [1]. However, in this paper, the loss comparison between 4 leg NPC and T-type converters is carried out according to different PWM methods.

II. PWM OF 4 LEG POWER CONDITIONING SYSTEMS

The continuous PWM (CPWM) method for 4 leg voltage source converter has been discussed in [3]. The offset voltage can be selected as (1). The CPWM is an optimal PWM in the view point of the harmonics and the switching frequency. But, it is well known that in 3 leg converter the discontinuous PWM (DPWM) may reduce the switching loss under the same harmonics with CPWM at higher modulation index [4]. Among various DPWM methods, the DPWM60° is the most efficient method and it can be simply implemented by changing offset voltage as (2)[2, 5] with carrier based PWM logic.

$$V_{fn}^* = \begin{cases} -\dfrac{V_{\max}}{2} & (V_{\min} > 0) \\ -\dfrac{V_{\min}}{2} & (V_{\max} < 0) \\ -\dfrac{V_{\max}+V_{\min}}{2} & (otherwise) \end{cases} \qquad (1)$$

$$V_{fn}^* = \begin{cases} \dfrac{V_{dc}}{2} - V_{\max} & (|V_{\min}| < |V_{\max}|) \\ -\dfrac{V_{dc}}{2} - V_{\min} & (|V_{\min}| > |V_{\max}|) \end{cases} \qquad (2)$$

, where $V_{\max} = \max(V_{af}^*, V_{bf}^*, V_{cf}^*)$ and $V_{\min} = \min(V_{af}^*, V_{bf}^*, V_{cf}^*)$.

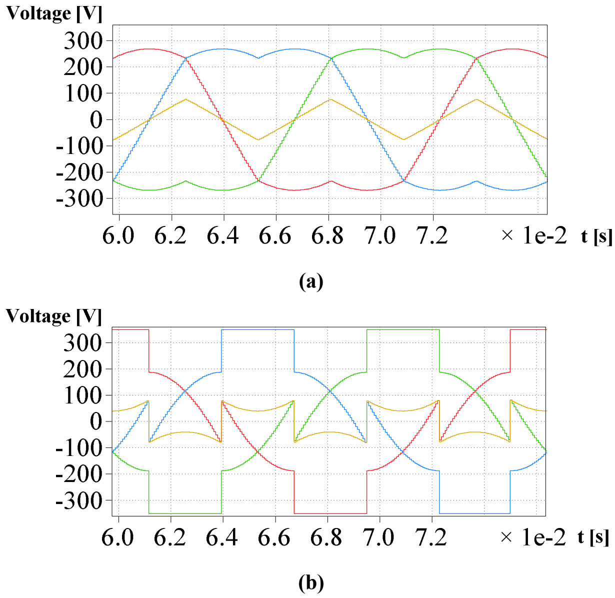


Figure 2. Offset voltage V_{fn}^* (yellow), Pole voltages V_{an}^* (green), V_{bn}^* (red), V_{cn}^* (blue) (a) CPWM, (b) DPWM 60°

It is the method to make the reference voltage be the maximum or minimum value for 60° of a period of the output frequency and not to switch during that period. The offset voltages of CPWM and DPWM60° are shown in Fig. 2.

III. LOSS ANALYSIS WITH SIMULATION

To evaluate the efficiency of each topology, simulations are executed using Matlab Simulink with PLECS. In PLECS, all the loss information (turn on/off loss and voltage drop with the current) can be fed by a table form in the switching device property as shown in Fig. 4. So the losses of the power switches can be calculated precisely before the experiments. The loss data of the Infineon F3L300R12PT4 is adopted. It is a module for T-type 1 leg, and it contains 600 V and 1200 V

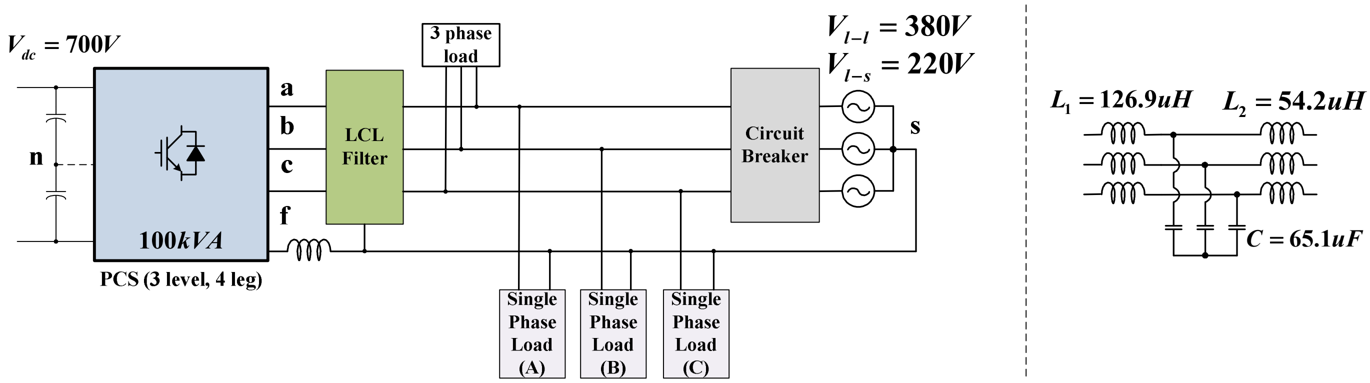


Figure 3. Total system configuration

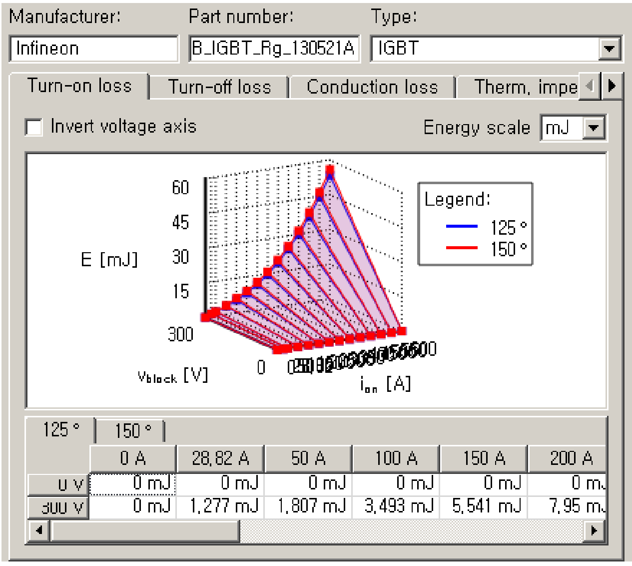
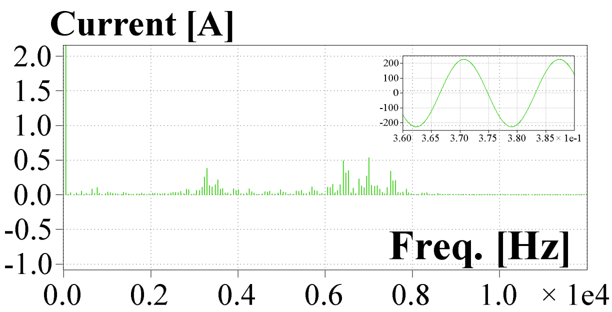


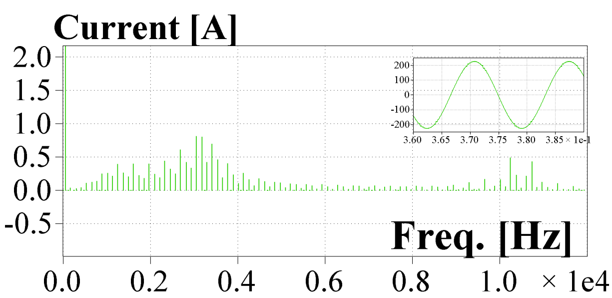
Figure 4. Power switch device loss table

device together. For fair comparison, only 600V device data was used to evaluate the efficiency of NPC topology.

The grid voltage is set as 3 phase 380 V_{rms} , and the dc link voltage as 700 V . The rated output power of PCS under consideration is 100 kVA. When CPWM is adopted, the switching frequency is set as 7 kHz to keep the harmonic regulation of the IEEE 519. For equal average switching frequency, the switching frequency at DPWM60° is increased to 10.5 kHz ($= 7\,kHz \times 3/2$) [6]. The harmonics of the currents

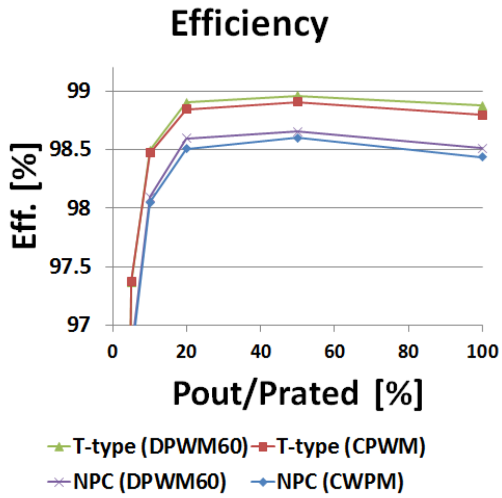


(a)

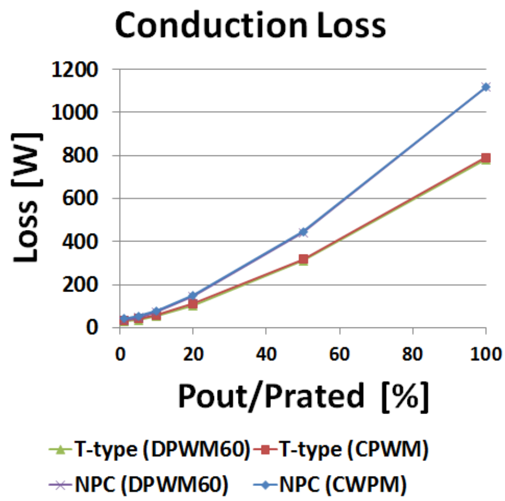


(b)

Figure 5. A phase current and its FFT
(a) T-type CPWM, (b) T-type DPWM60 °



(a)



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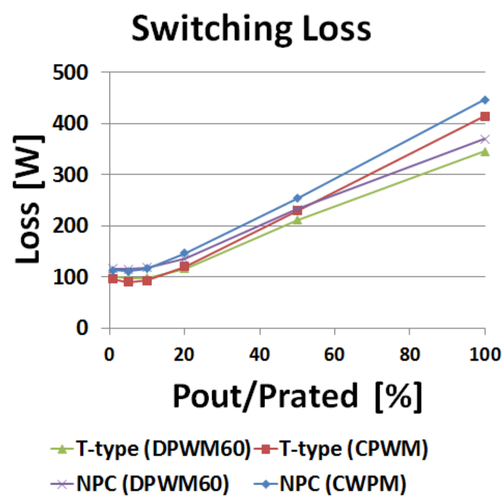
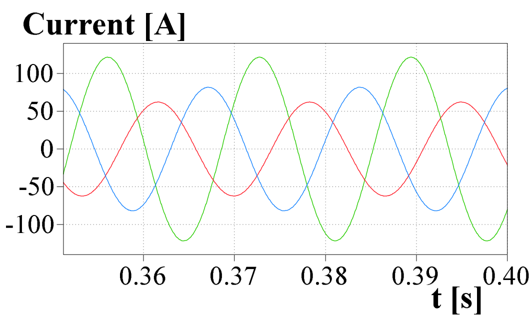
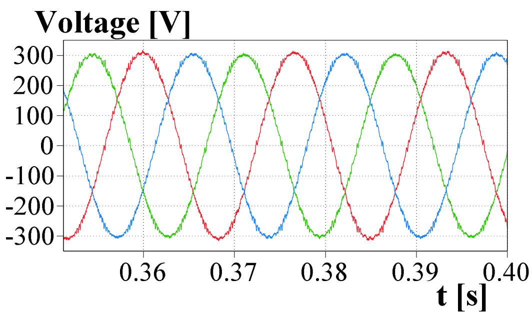


(c)

Figure 6. Efficiency (a) and losses (b, c) of the 4 leg 3 level topologies at normal state



(a)



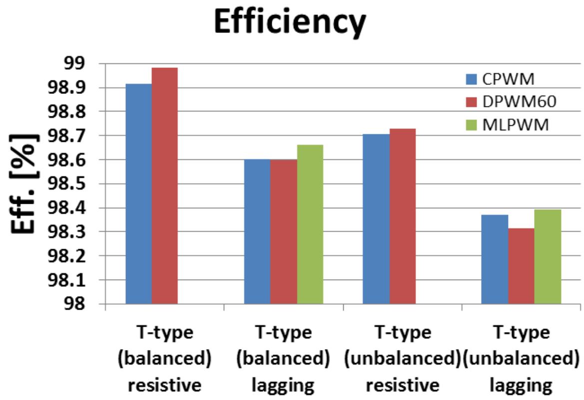
(b)

Figure 7. Stand-alone operation
(a) Phase current, I_{as} (green), I_{bs} (red), I_{cs} (blue),
(b) Phase voltage, V_{as} (green), V_{bs} (red), V_{cs} (blue)

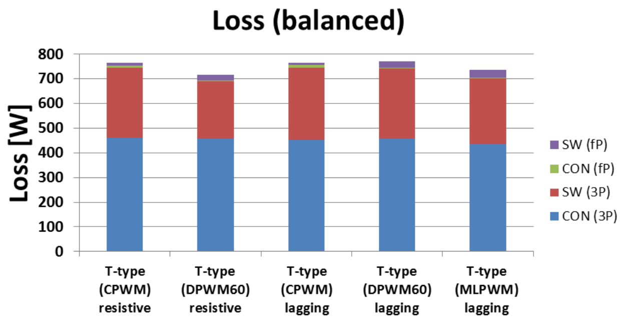
of CPWM and DPWM60° are both under the limit at each harmonic frequency as shown in Fig. 5.

At normal state when the switches of the circuit breaker are closed in Fig. 3, the efficiency of the T-type is higher than that of the NPC as shown in Fig. 6. While two power switches are conducting during upper or lower arm "on" state in case of the NPC, only one switch is conducting in case of the T-type. While the conduction loss is almost the same in each topology, the switching loss of the DPWM60° is smaller even though the averaging switching frequency is the same. Therefore, the efficiency of DPWM60° is a little higher than that of CPWM as expected.

To confirm that the 4 leg PCS works well under unbalanced loads at stand-alone operation, unbalanced single phase lagging loads (power factor = 0.8) are used ($Z_a = 1.61 + j1.18\Omega$, $Z_b = 3.22 + j2.36\Omega$, $Z_c = 2.41 + j1.76\Omega$). The switches of the circuit breaker are open. In Fig.7, although the three phase loads are unbalanced, the single phase voltages applied to each loads are balanced to $220V_{rms}$. To analyze the loss at stand-alone operation, simulation is implemented in various kinds of load conditions listed in Table I. The impedances of the lagging loads were determined to have 0.8 power factor and same current magnitude as the resistive loads case. The modulation index is 0.8865. The efficiency of the T-type is higher than that of the NPC as in case of the normal state regardless of the load conditions. From Fig. 8 (a), it can be seen that the efficiency is dependent on the load conditions.



(a)



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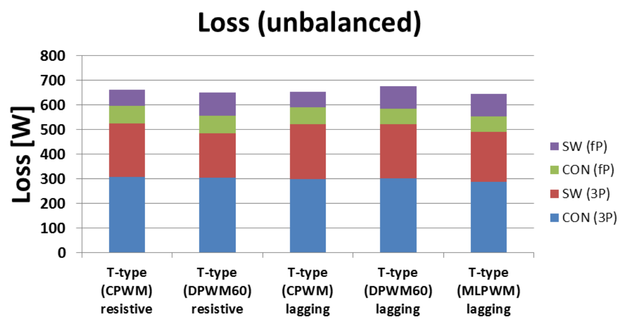

(c)

Figure 8. Efficiency (a) and losses (b, c) of 4 leg T-type at stand-alone operation.

When the loads are resistive, the efficiency of the DPWM60° is higher. However, if the loads are lagging, the result is vice versa. From the loss analysis results in Fig. 8. (b), (c), it is noted that the increase in the "f" phase switching loss is almost constant when PWM method is changed from CPWM to DPWM60°. But the decrease in the 3 phase switching loss of the lagging loads is smaller. In case of using DPWM60°, the larger the phase difference between the voltage and the current is, the smaller saving of the switching loss is. Under this consideration, if the non-switching period of DPWM is adjusted according to the phase shift between voltage and current, the saving of the switching loss of DPWM60° could be maximized [7]. The PWM method is called MLPWM (Minimum Loss PWM) and is based on the DPWM60°. In Fig. 8 (b), (c), the 3 phase switching loss of MLPWM is much smaller than that of DWPM60°. It is because the non-switching period of DPWM is changed according to the phase of the current. As a result, the efficiency of the MLPWM is higher in case of the lagging loads.

TABLE I. LOAD CONDITIONS (SIMULATION)

Load Conditions	$Z_a [\Omega]$ (p.u.)	$Z_b [\Omega]$ (p.u.)	$Z_c [\Omega]$ (p.u.)
Balanced Resistive	2 (1.4)	2 (1.4)	2 (1.4)
Balanced Lagging	1.61+ j1.18 (1.1+ j0.8)	1.61+ j1.18 (1.1+ j0.8)	1.61+ j1.18 (1.1+ j0.8)
Unbalanced Resistive	2 (1.4)	4 (2.9)	3 (2.2)
Unbalanced Lagging	1.61+ j1.18 (1.1+ j0.8)	3.22+ j2.36 (2.3 + j1.7)	2.41 + j1.76 (1.7+ j1.2)

IV. EXPERIMENTAL RESULT

The configuration of the system, aforementioned in Fig. 3, is implemented as Fig. 9. But it is downsized to 5kVA 4 leg T-type system. The grid voltage is 220 V_{rms} (line-to-line). From Fig. 11 (a), the maximum efficiency runs into 98.15% at grid-connected operation mode in case of T-type 4 leg system. Although the three phase loads are unbalanced, the single phase voltages applied to each loads are balanced to 127 V_{rms} as shown in Fig.10. Also various kinds of PWM methods are applied for stand-alone operation when lagging loads exist as listed in Table II. In Fig. 11 (b), the efficiency of the MLPWM is 0.26 ~ 0.34% higher than that of the CPWM in case of lagging loads.

TABLE II. LOAD CONDITIONS (EXPERIMENT)

Load Conditions	$Z_a [\Omega]$ (p.u.)	$Z_b [\Omega]$ (p.u.)	$Z_c [\Omega]$ (p.u.)
Balanced Lagging	40+ j24.8 (4.3+ j2.7)	40+ j24.8 (4.3+ j2.7)	40+ j24.8 (4.3+ j2.7)
Unbalanced Lagging	40+ j24.8 (4.3+ j2.7)	20+ j12.4 (2.15+j1.35)	OPEN

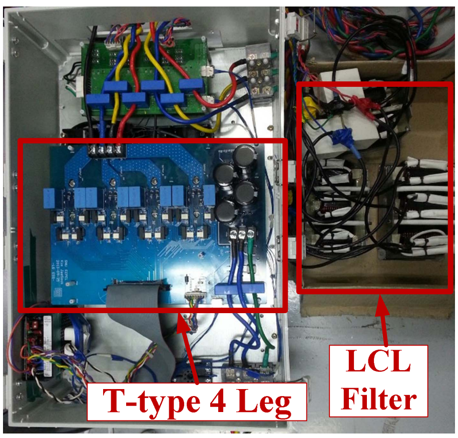

Figure 9. Experimental set-up

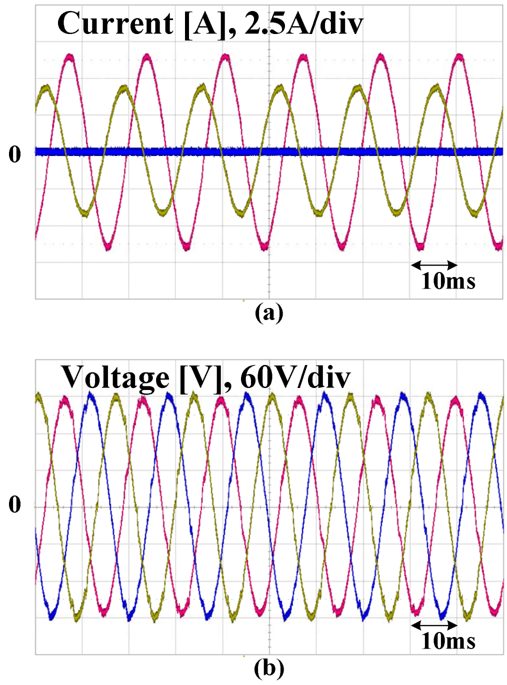

Figure 10. Stand-alone operation,
(a) Phase current, I_{as} (yellow), I_{bs} (red), I_{cs} (blue),
(b) Phase voltage, V_{as} (yellow), V_{bs} (red), V_{cs} (blue)

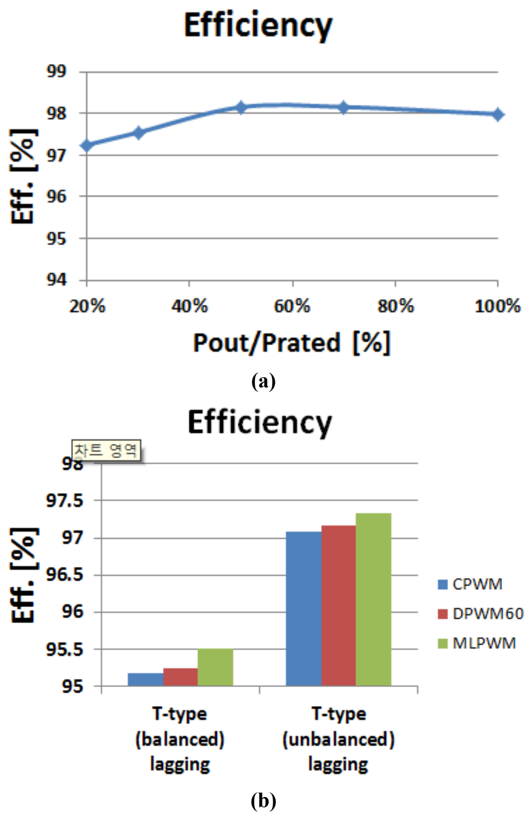

Figure 11. Experimental result - Efficiency
(a) at grid-connected operation mode
(b) at stand-alone operation mode

V. CONCLUSIONS

In this paper, loss analysis was carried out for 3 level 4 leg PCS. Under the consideration of stand-alone operation of PCS for unbalanced 3 phase loads, 3 level 4 leg PCS has been chosen. Based on the real loss data table, simulations has been carried out in each topology and each PWM method before the experiments. From the simulation and experimental results, it was shown that T-type topology with MLPWM is the most efficient combination regardless of whether the loads are balanced or not.

ACKNOWLEDGMENT

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