A Comparative Study of Voltage Gain Tolerance in Conventional and Three-level LLC Converters against Circuit Variation

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Abstract- This paper clarifies the relationship between voltage gain tolerance and normalized design parameters against resonant circuit components variation for mass production of LLC converters and three-level LLC converters. The LLC converter is an attractive solution for high power application, hence many photovoltaic systems which use LLC converter have been proposed. The multi-level LLC converter is also proposed to overcome a drawback of the conventional LLC converter. It is important on mass production stage to clarify the relationship between its voltage gain tolerance and design parameters against resonant circuit component variations, however it has rarely studied. Therefore, we study the relationship between voltage gain tolerance and three normalized design parameters related to the resonant circuit with Monte Carlo simulation. As a result, it has found that a conventional LLC converter and a three-level LLC converter have approximately same voltage gain tolerance characteristics. However the three-level LLC converter has a superior performance compared to the conventional LLC converter in aspect of the voltage gain tolerance. The reason for a difference of the performance comes from a design constraint. By utilizing this knowledge, designers can reduce unnecessary losses of the conventional and the three-level LLC converter which are generated by too much voltage gain margin; therefore this paper can contribute to improving performance in renewable energy generation systems.

Keywords tolerance; variation; three-level; LLC; Monte Carlo.

Nomenclature

C_R	Resonant capacitor and its capacitance
L_{R1}	Primary resonant inductor and its inductance
L_{R2}	Secondary resonant inductor and its inductance
L_M	Magnetizing inductance
n	Transformer turns ratio: primary turns/secondary turns
L_R	Resonant inductance: $L_{R1}+n^2L_{R2}$
V_{IN}	Input voltage
V_{OUT}	Output voltage
M	Voltage gain: nV_{OUT}/V_{IN}
V_{AB}	Output voltage of the full bridge circuit
f_R	Resonant frequency: $1/(2\pi\sqrt{(L_RC_R)})$
f_{SW}	Switching frequency
f_N	Normalized switching frequency: f_{SW}/f_R
L_N	Inductance ratio: L_R/L_M
Z_O	Characteristic impedance: $\sqrt{(L_R/C_R)}$
R_{OUT}	Load resistance
R_{AC}	Reflected R_{OUT}: $8n^2/\pi^2*R_{OUT}$
Q	Quality factor: Z_O/R_{AC}
D	Master duty

1. Introduction

Renewable energy has been widely recognized as one of the most effective solutions to reduce fossil-fuel consumption and greenhouse gas emissions. Among the renewable energy sources, the solar energy generation is recognized as an important energy source. There are some studies which use LLC converter in photovoltaic systems [1-6], and it is a common issue to design the LLC converter to keep its performance with sufficient output voltage when values of resonant circuit components vary in the field. This issue is particularly important for the photovoltaic system which has no boost converter and the LLC converter is directly connected to photovoltaic panels, because the input voltage range of the converter is wide and it makes difficult to design the converter.

The combination of the LLC converter and the multi-level conversion technique is proposed to overcome a drawback of the LLC converter [7-13]. The three-level LLC converter proposed in [8] can control the output power at a fixed frequency, and its rectifier diodes have a ZCS capability under wide input to output voltage ratio variation. In addition to such advantages, the conduction loss of the converter can be reduced by the three-level conversion circuit because low-voltage-rating power semiconductors can be used.

We already studied the relationship between voltage gain tolerance and design parameters against resonant circuit components variation of the LLC converter [14]. This paper describes the relationship between voltage gain tolerance and design parameters of the three-level LLC converter compared to the conventional LLC converter. The procedure of an analysis is described in section 2, and the result of the analysis is shown in section 3. Conclusion is provided in section 4.

2. Procedure of Analysis

2.1. Target Converter and output voltage of full-bridge circuit

The target converter of the analysis in this paper is shown in Fig. 1. This topology is a hybrid full-bridge three-level LLC resonant converter [8]. The voltage between points A and B in Fig. 1 is the output voltage of the full-bridge circuit. The waveforms of this voltage (V_{AB}) are shown in Fig. 2. When a master duty is 90%, it has 80% duty of $\pm V_{IN}$ and 20% duty of $\pm 1/2V_{IN}$. The master duty is defined in [13]. When a master duty is 100%, V_{AB} has 100% duty of $\pm V_{IN}$; therefore this converter operates as a conventional LLC converter when master duty is 100%.

2.2. Viewpoints of Analysis

The problems caused by variations in the resonant circuit components are the following two cases.

(A). The output voltage is too low at a rated power and minimum input voltage.

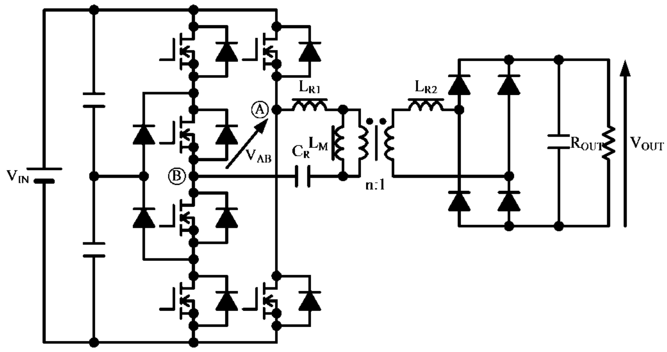
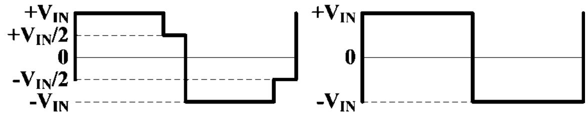


Fig. 1. Hybrid full-bridge three-level LLC resonant converter.



(a). Master duty = 90% (b). Master duty = 100%

Fig. 2. Waveform of V_{AB}.

(B). The output voltage is too high at no load and maximum input voltage.

The three-level LLC converter can decrease the output voltage to zero by decreasing the master duty to zero; therefore it is not necessary to consider the case (B). The voltage gain of the conventional LLC converter obtained by first harmonic approximation is known as Eq. (1) [15]. By assigning zero to Q and infinite to f_N, M in case (B) is calculated as Eq. (2). Related parameter in Eq. (2) is only L_N, therefore detailed analysis is not required in case (B).

From the above, the analysis in this paper is performed considering only case (A).

$$M = \frac{1}{\sqrt{\left(1 + L_N - \frac{L_N}{{f_N}^2}\right)^2 + Q^2\left(f_N - \frac{1}{f_N}\right)^2}} \tag{1}$$

$$M = \frac{1}{1 + L_N} \tag{2}$$

2.3. Procedure of Analysis

We use normalized parameters for input and output parameters of the analysis to obtain a versatility, however varying parameters in the field are real values such as inductance or capacitance. Therefore the analysis is performed in following steps. Step 5 is necessary to make the output power to be constant. The circuit simulator used in this analysis is SCAT (Switching Converter Analysis Tool) [16].

1. Calculate C_R from n, f_R, Q and R_{OUT} using Eq. (3).
2. Calculate L_R from C_R and f_R using Eq. (4).

3. Calculate L_M from L_R and L_N using Eq. (5).
4. Create samples which have a normal distribution with a predetermined standard deviation and typical value calculated in step 1 to 3 using a random number.
5. Set typical value of C_R, L_R and L_M to the component of the circuit simulator and regulate V_{IN} to have specified V_{OUT}.
6. Set each value of the sample set to the component of the circuit simulator.
7. Calculate voltage gain M from V_{IN}, n, and V_{OUT} whose value is obtained from circuit simulation in steady state.
8. Calculate standard deviation from obtained set of M, and calculate tolerance of M from standard deviation.

Equations from (3) to (5) are obtained from definitions of normalized parameters.

L_{R1} and L_{R2} are assumed to be a transformer leakage inductor. It is also assumed that they are evenly distributed. Therefore they are calculated by Eq. (6).

$$C_R = \frac{\pi}{16n^2 f_R Q R_{OUT}} \tag{3}$$

$$L_R = \frac{1}{C_R}\left(\frac{1}{2\pi f_R}\right)^2 \tag{4}$$

$$L_M = \frac{L_R}{L_N} \tag{5}$$

$$L_{R1} = n^2 L_{R2} = L_R/2 \tag{6}$$

2.4. Parameters used in Analysis

Circuit parameters used in the analysis are shown in Table 1. Considering case (A) for the conventional LLC converter, f_N is a minimum value which is limited by a controller. Therefore its values are selected to be lower than unity. In the case of three-level LLC converter, f_N is a fixed value and designers can select it at their will. Therefore, selected values include around unity.

Parameters related to the Monte Carlo method are shown in Table 2. All tolerances of L_R, L_M and C_R are assumed to ±7% and they correspond to ±3σ. It means that process capability index of the parts is estimated to be one. The voltage gain tolerance also corresponds to ±3σ. It means that process capability index of the voltage gain is set to be one.

3. Result of Analysis

The result of the analysis is shown in Fig. 3 which compares the conventional LLC converter to the three-level LLC converter, and Fig. 4 for the three-level LLC converter.

Table 1. Circuit parameters used in analysis.

D	100% for LLC 90% for 3-level LLC
Q	0.20, 0.25, 0.30, … , 0.90, 0.95, 1.00
L_N	0.100, 0.125, 0.150, … , 0.450, 0.475, 0.500
f_N	0.50, 0.55, …, 0.80, 0.85 for LLC 0.50, 0.55, …, 1.05, 1.10 for 3-level LLC
f_R	100kHz
n	1
V_{OUT}	380V
R_{OUT}	19Ω

Table 2. Parameters for Monte Carlo analysis.

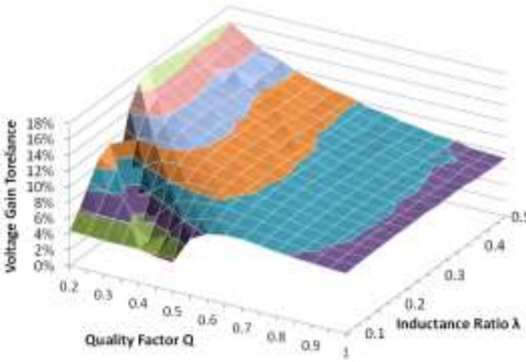
Number of samples	1,000
Tolerance of C_R, L_R and L_M	±7%
Tolerance above / standard deviation	3
Voltage gain tolerance / standard deviation	3

From Fig.3, it is clear that the voltage gain tolerance characteristics of both converters are very similar except the width of the valley of the voltage gain tolerance. This is because the waveform of V_{AB} at master duty is equal to 90% is similar to the conventional LLC converter's waveform. Assuming the case (A), the master duty becomes a maximum value. 90% is supposed as a maximum value.

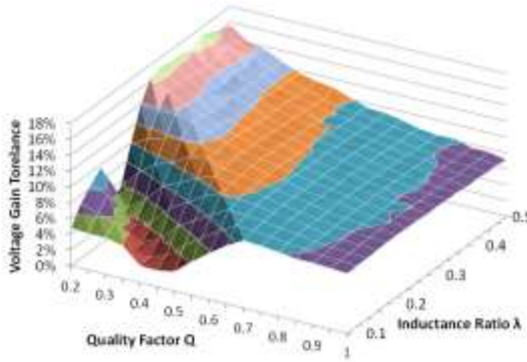
To minimize the voltage gain tolerance, f_N should be around unity. The three-level LLC converter is advantageous in this aspect, because the switching frequency is fixed and a designer can select an advantageous value. In the case of the conventional LLC converter, a minimum f_N is constrained to be a lower value when the input voltage range or the output voltage range is wide. The value of a minimum f_N of the conventional LLC converter depends on environmental conditions.

When f_N is around unity, L_N should be a small value to minimize the voltage gain tolerance. Q does not have a big impact for it. The conventional LLC converter has a constraint of L_N considering the case (B) which is represented in Eq. (2); therefore L_N cannot become to be a small value. The three-level LLC converter also has a constraint of L_N, but it only relates to the ZVS condition. Therefore L_N can become to be a small value. For example L_N is 0.0737 in [13].

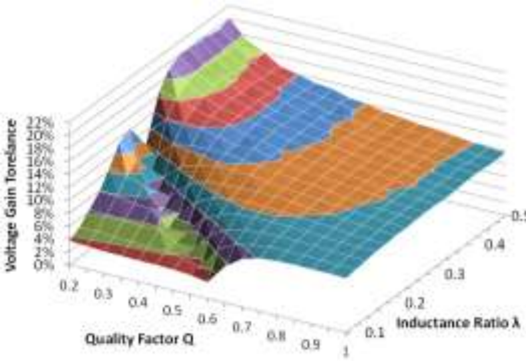
When f_N is lower than unity, linear area where the voltage gain tolerance becomes to be small appears in the Q - L_N plane. This area is called as 'voltage gain tolerance valley' in [14]. The location of the valley depends on f_N. Therefore a designer should select a combination of Q and L_N to place the design point in this area in accordance with a minimum f_N.



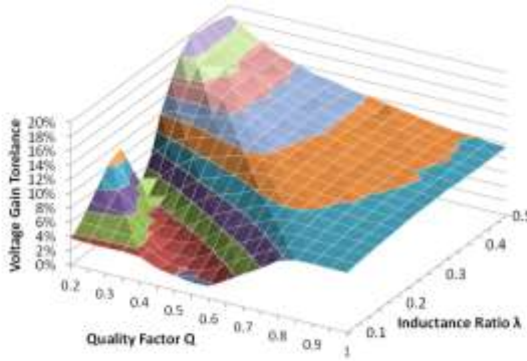
(a1). LLC converter at $f_N = 0.50$



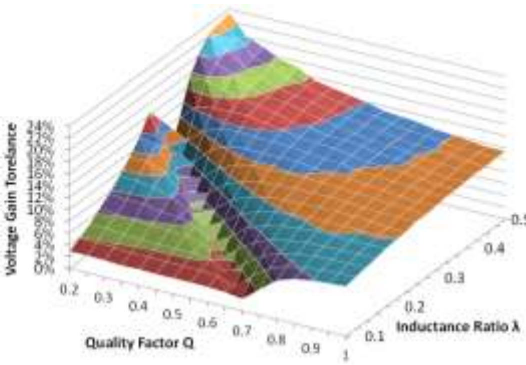
(a2). 3-level LLC converter at $f_N = 0.50$



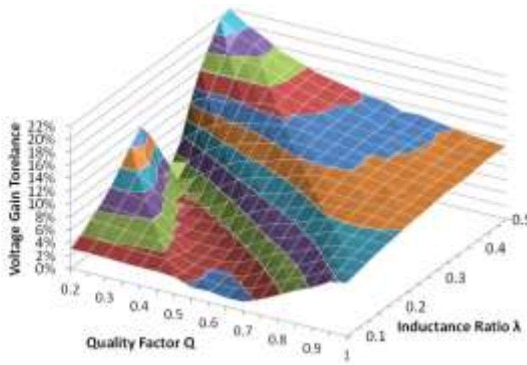
(b1). LLC converter at $f_N = 0.55$



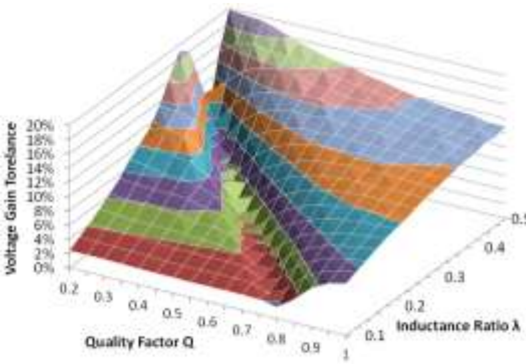
(b2). 3-level LLC converter at $f_N = 0.55$



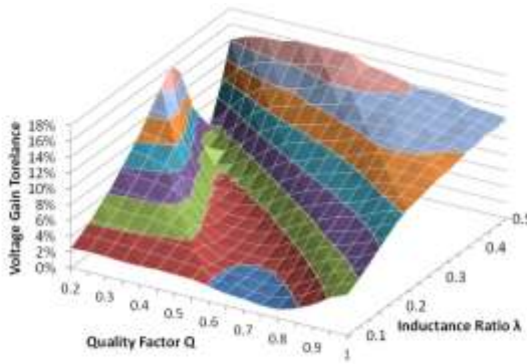
(c1). LLC converter at $f_N = 0.60$



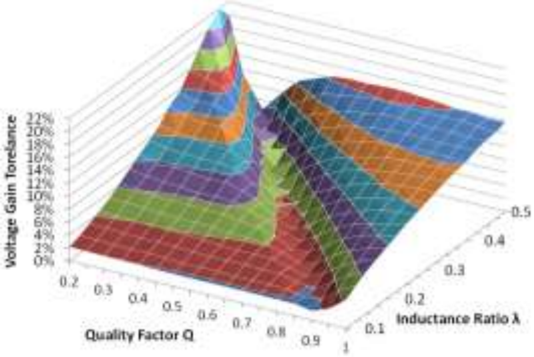
(c2). 3-level LLC converter at $f_N = 0.60$



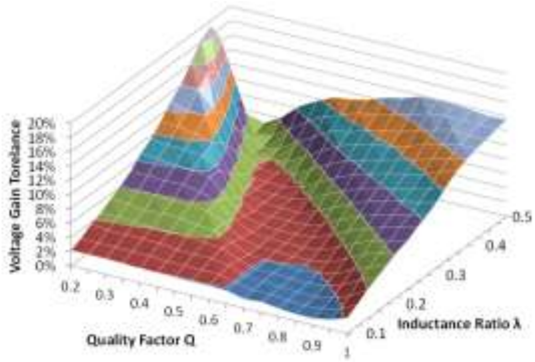
(d1). LLC converter at $f_N = 0.65$



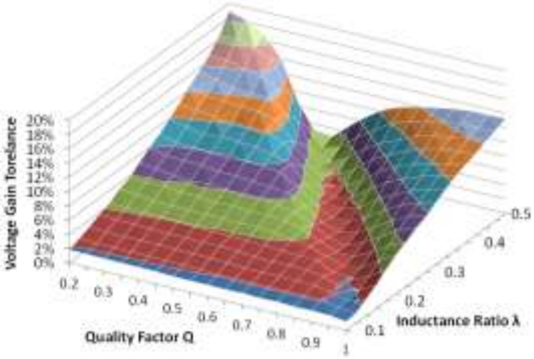
(d2). 3-level LLC converter at $f_N = 0.65$



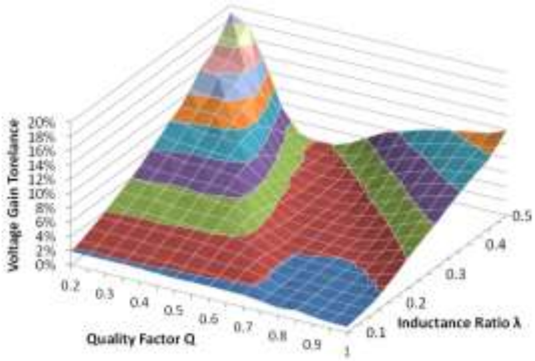
(e1). LLC converter at $f_N = 0.70$



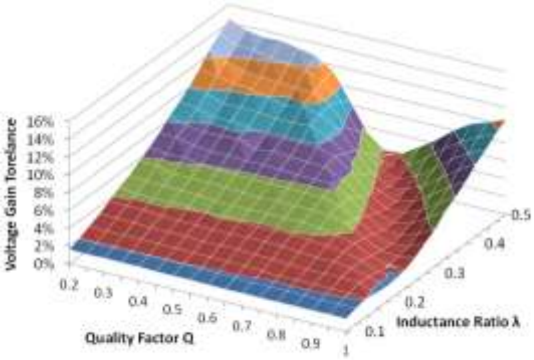
(e2). 3-level LLC converter at $f_N = 0.70$



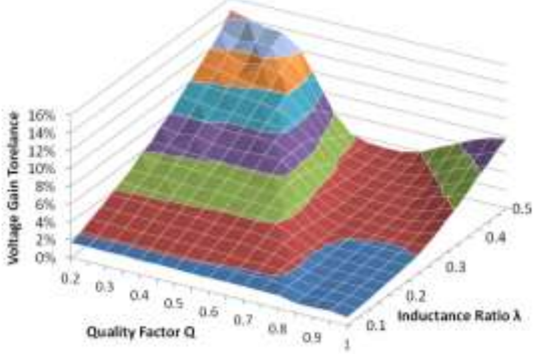
(f1). LLC converter at $f_N = 0.75$



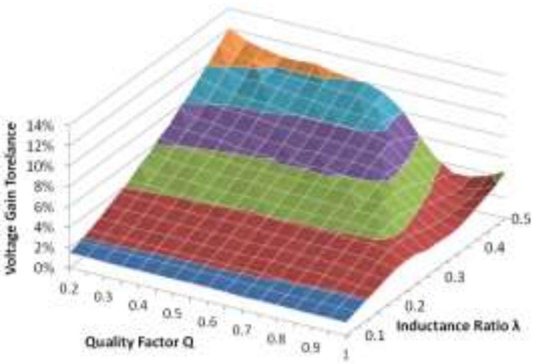
(f2). 3-level LLC converter at $f_N = 0.75$



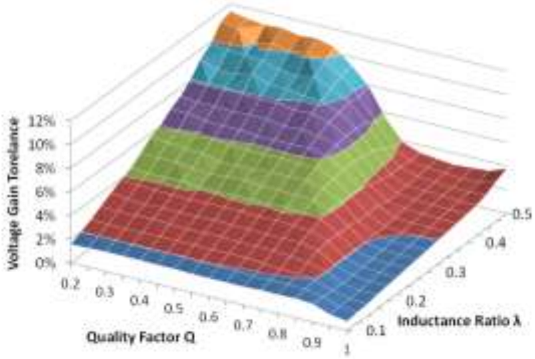
(g1). LLC converter at $f_N = 0.80$



(g2). 3-level LLC converter at $f_N = 0.80$

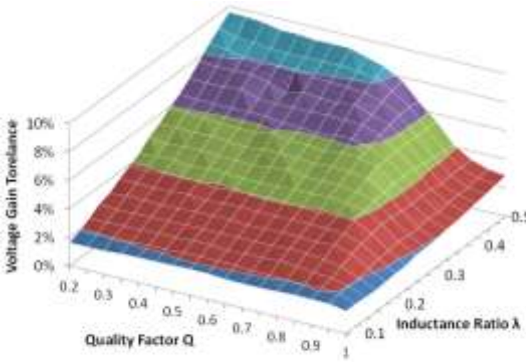


(h1). LLC converter at $f_N = 0.85$

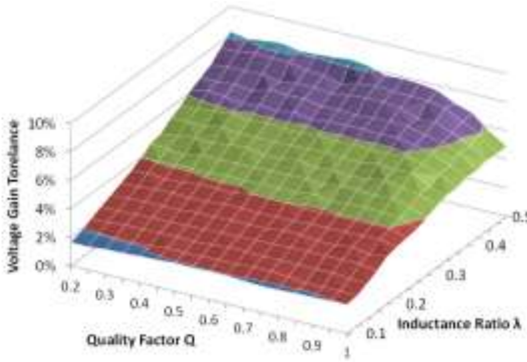


(h2). 3-level LLC converter at $f_N = 0.85$

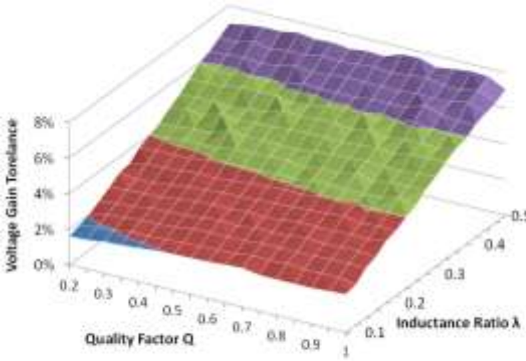
Fig. 3. Tolerance of voltage gain vs quality factor and inductance ratio taking normalized frequency and converter topology as a parameter.



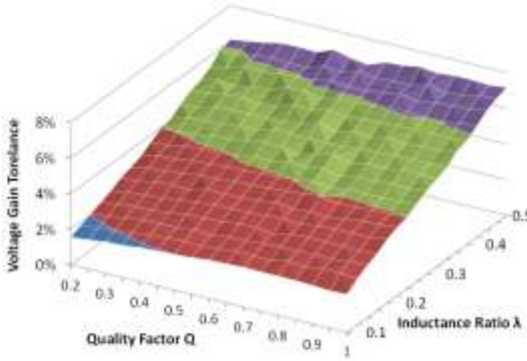
(a). f_N = 0.90



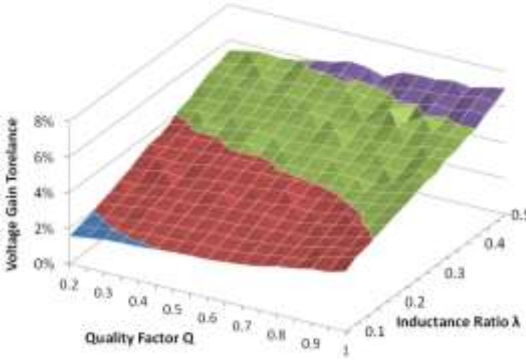
(b). f_N = 0.95



(c). f_N = 1.00



(d). f_N = 1.05



(e). f_N = 1.10

Fig. 4. Tolerance of voltage gain vs quality factor and inductance ratio taking normalized frequency as a parameter about three-level LLC converter.

4. Conclusion

This paper describes the relationship between voltage gain tolerance and normalized design parameters against resonant circuit variation of a three-level LLC converter and a conventional LLC converter by Monte Carlo method using circuit simulation.

It is found that the three-level LLC converter has a superior performance compared to the conventional LLC converter in aspect of the voltage gain tolerance despite the similar voltage gain tolerance characteristics. The reason for a difference of the performance comes from a design constraint. The switching frequency of the three-level LLC converter is fixed and it is not constrained by environmental conditions, therefore designer can select an advantageous value. Furthermore the three-level LLC converter can decrease an inductance ratio. It also minimizes the voltage gain tolerance. By utilizing this knowledge this paper can contribute to improving performance in renewable energy generation systems.

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