직류 마이크로그리드 시스템의 고조파 상태 공간 모델링

영남대학교 전기공학과

Harmonic State Space Modeling of DC Microgrid Systems

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ABSTRACT

This paper proposes a harmonic state space (HSS) modeling of DC microgrid. In the HSS model, nonlinear equations for the switched circuit model are transformed into multiple linear equations. The simulation results have shown the HSS modeling is comparable with PSIM simulation.

1. Introduction

Modeling of power electronic converters has been used for the purpose of analyzing the converters and designing the corresponding controllers. For DC/DC converters, the most widely used modeling method is the average model where only DC component is considered. Also, Generalized Average Model (GAM) has been introduced to consider other harmonics. However, when multiple harmonic components are included, the equations become nonlinear, so the ability of this method is limited [1]. In a power electronic system which has some switching components, the harmonics may interact with each other. Besides, the harmonic components may interfere with the controller, hence they should be considered in designing the controller. To include higher order harmonics in modeling, Harmonic State Space (HSS) method has been proposed [2]. In this work, a DC microgrid is modeled with HSS method, of which results are compared those from PSIM simulation. By comparison, the accuracy of the HSS model is verified.

2. DC Microgrid Model

The DC microgrid modeled in this study is shown in Fig.1. In this microgrid, a PWM rectifier, a buck converter, a boost converter, a PWM inverter, and also a resistive load are connected to the DC bus. In this figure, it is assumed that the PWM rectifier feeds the bus but other converters are being fed from the bus.

To develop an HSS model, it is needed to derive the switched model of the system. In switched model, the dominating differential equations in various switching states of the converters are represented in some lumped expressions containing system variables and switching signals. Here, the switched model of the converters existing in the DC microgrid are expressed in Laplace domain. For the PWM rectifier:

$$I_{a1} = \frac{+2(V_{a1}-U_{a1}*V_{bus})-(V_{b1}-U_{b1}*V_{bus})-(V_{c1}-U_{c1}*V_{bus})}{3(L_1 s+R_1)} \quad (1)$$

$$I_{b1} = \frac{-(V_{a1}-U_{a1}*V_{bus})+2(V_{b1}-U_{b1}*V_{bus})-(V_{c1}-U_{c1}*V_{bus})}{3(L_1 s+R_1)} \quad (2)$$

$$I_{c1} = \frac{-(V_{a1}-U_{a1}*V_{bus})-(V_{b1}-U_{b1}*V_{bus})+2(V_{c1}-U_{c1}*V_{bus})}{3(L_1 s+R_1)} \quad (3)$$

$$I_{o1} = U_{a1}*I_{a1}+U_{b1}*I_{b1}+U_{c1}*I_{c1} \quad (4)$$

where U_{a1}, U_{b1}, and U_{c1} are the gate signals of the PWM rectifier which are either 0 or 1 and other variables are as Fig. 1.

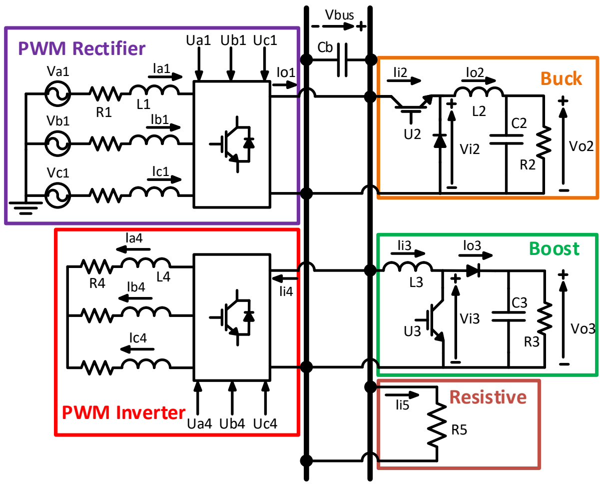


Fig. 1. DC microgrid under study.

For the other converters, the gate signals and variables are as shown in Fig.1.

For buck converter:

$$V_{i2} = U_2 * V_{bus} \quad (5)$$

$$I_{o2} = V_{i2} * \frac{R_2 C_2 s+1}{L_2 C_2 s^2+L_2 s+R_2} \quad (6)$$

$$I_{i2} = U_2 * I_{o2} \quad (7)$$

$$V_{o2} = V_{i2} * \frac{R_2}{L_2 C_2 s^2+L_2 s+R_2} \quad (8)$$

For the boost converter,

$$I_{i3} = \frac{V_{bus}-V_{i3}}{L_3 s} \quad (9)$$

$$I_{o3} = (1-U_3)*I_{i3} \quad (10)$$

$$V_{i3} = (1-U_3)*V_{o3} \quad (11)$$

$$V_{o3} = I_{o3} * \frac{R_3}{R_3 C_3 s+1} \quad (12)$$

For the PWM inverter,

$$I_{a4} = \frac{+2U_{a4}-U_{b1}-U_{c1}}{3(L_4 s+R_4)} * V_{bus} \quad (13)$$

$$I_{b4} = \frac{-U_{a4}+2U_{b1}-U_{c1}}{3(L_4 s+R_4)} * V_{bus} \quad (14)$$

$$I_{c4} = \frac{-U_{a4}-U_{b1}+2U_{c1}}{3(L_4 s+R_4)} * V_{bus} \quad (15)$$

$$I_{i4} = U_{a4}*I_{a4}+U_{b4}*I_{b4}+U_{c4}*I_{c4} \quad (16)$$

For the resistive load and DC bus,

$$I_{i5} = \frac{V_{bus}}{R_5} \quad (17)$$

$$V_{bus} = \frac{I_{o1}-I_{i2}-I_{i3}-I_{i4}-I_{i5}}{C_b s} \quad (18)$$

3. HSS Model of DC Microgrid

HSS model of the DC microgrid is developed based on the switched model in section 2. There are some steps to do it. The first step is to determine the fundamental frequency and the desired harmonic orders. Here, the fundamental frequency is 50 Hz and the harmonic orders 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 38, 40, 42, 77, 79, 80, 81, 83, 120, 160, 200, and 240 are considered in the HSS model. The second step is to convert all the equations into harmonic-domain. For that, all the variables should be represented with vectors containing the complex Fourier series coefficients of the variables. For example, harmonic vector of the DC bus voltage is expressed as

$$V_{bus} = [\,V_{bus-240} \cdots \; V_{bus-1} \;\; V_{bus0} \;\; V_{bus+1} \;\; \cdots \;\; V_{bus+240}\,]^T \quad (19)$$

In this representation, $V_{bus+1}$is the harmonic coefficient of the first harmonic and V_{bus-1} is the conjugate of V_{bus+1}. In addition, as the multiplication in time domain is equal to a convolution in frequency domain and the convolution in frequency domain can be implemented with Toeplitz matrix, all the switching signals should be replaced by their corresponding Toeplitz matrices [3]. For instance, if U_2 is the harmonic vector of buck converter gate signal, the Toeplitz matrix of U_2 is as follow:

$$\Gamma(U_2) = \begin{bmatrix} U_{2\_0} & U_{2\_-1} & . & . & U_{2\_-240} & 0 & . & . & 0 \\ U_{2\_+1} & U_{2\_0} & U_{2\_-1} & . & . & U_{2\_-240} & 0 & . & . \\ . & U_{2\_+1} & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & 0 \\ U_{2\_+240} & . & . & . & . & . & . & . & U_{2\_-240} \\ 0 & U_{2\_+240} & . & . & . & . & . & . & . \\ . & 0 & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . & U_{2\_-1} \\ 0 & . & . & 0 & U_{2\_+240} & . & . & U_{2\_+1} & U_{2\_0} \end{bmatrix} \quad (20)$$

The third step is to perform matrix calculations iteratively based on the developed equations in frequency domain. Finally, it is needed to convert the results from harmonic domain into time domain using (21),

$$x(t) = \sum_{K\in Z} X_K e^{jK\omega_0 t} \quad (21)$$

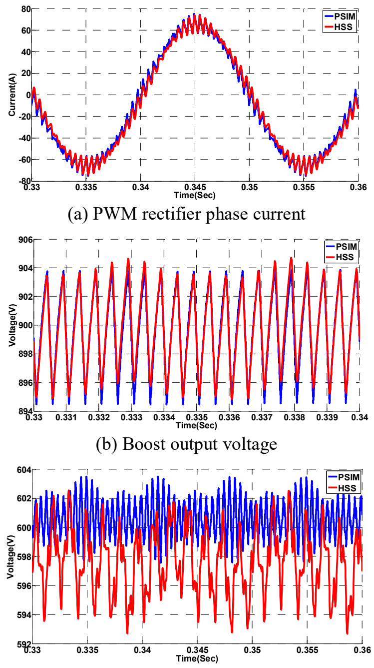
where, K is the related harmonic order.

4. Simulation Results

The HSS model with the parameters listed in Table 1 has been simulated in Matlab/Simulink. The results are compared with those from PSIM simulation. Fig. 2(a) and (b) show PWM rectifier phase current and output voltage of the boost converter, respectively. As can be seen, two results are similar each other. Also, in Fig. 2(a), DC bus voltage is shown but there is a minor difference between these two results due to the truncated harmonic spectrum in the HSS model. This difference can be decreased if higher order harmonics are taken into account.

Table 1 Design parameters of DC microgrid

parameter	value		parameter	value
Line voltage	380V,50Hz		R_4	10 Ω
R_1	0.1 Ω		L_4	20 mH
L_1	2 mH		R_5	72 Ω
L_2	5 mH		DC bus voltage	600 Vdc
C_2	100 µF		C_b	1 mF
R_2	4.5 Ω		Switching freq.	2 KHz
V_{o2}	150 VDC		P(PWM rectifier)	30 KW
L_3	20 mH		P(buck)	5 KW
C_3	200 µF		P(boost)	10 KW
R_3	81 Ω		P(PWM inverter)	10 KW
V_{o3}	900 VDC		P(resistive)	5 KW



(a) PWM rectifier phase current

(b) Boost output voltage

(c) DC bus voltage

Fig. 2. Comparison between HSS and PSIM simulation results.

To have a quantitative evaluation in comparison, the following error index has been defined:

$$index = \frac{\sqrt{\frac{1}{T}\int_0^T (X_{PSIM}-X_{HSS})^2 dt}}{\sqrt{\frac{1}{T}\int_0^T (X_{PSIM})^2 dt}} \times 100 \quad (22)$$

where X can be any of the variables and T is the period of fundamental frequency. Using (22), the error index for PWM rectifier phase current, boost output voltage, and DC bus voltage are 2%, 1%, and 0.05% respectively which is satisfactory.

5. Conclusions

In this study, the harmonic model of a DC microgrid has been developed using HSS method. The model has been achieved by transforming switched model equations into harmonic-domain and representing all the variables with their Fourier coefficient vectors. Comparing the results from the HSS model with those from PSIM shows a high degree of accuracy of the HSS model. As ESS is an essential element in a DC microgrid, it will be included in the modeling of future works. The developed model can be used for the purpose of analyzing the behavior of harmonics in the DC microgrid.

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References

[1] J.-B. Kwon, X. F. Wang, F. Blaabjerg, and C. L. Bak, “Frequency domain modeling and simulation of DC power electronic systems using harmonic state space method,” IEEE Trans. Power Electron., vol. 32, pp.1044-1055, 2017.

[2] J.-B. Kwon (2017). Harmonic state space (HSS) modeling for power electronic based power systems. Aalborg Universitetsforlag. Ph.d.-serien for Det Ingeniør- og Naturvidenskabelige Fakultet, Aalborg Universitet.

[3] James Ernest Ormrod 2013, Harmonic state space modelling of voltage source converters, University of Canterbury, Christchurch, New Zealand.