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Research on Control Strategy of 2-phase Interleaving Magnetic Integrated VRM

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ABSTRACT

A kind of 2-phase interleaving coupled magnetic integrated VRM is studied and the corresponding passivity-based control strategy is put forward. The model of this kind of magnetic integrated VRM is constructed, and the performance of this 2-phase interleaving magnetic integrated VRM of passivity-based control is verified by simulation experiments. The results proved that this kind of passivity-based control strategy can decrease the steady state current ripple and the dynamic output voltage under load disturbance.

Keywords: VRM; Magnetic Integrated; Interleaving; Coupled Inductors

1. Introduction

Nowadays, the topology used in VRM is mostly multi-phase interleaving Buck converter, in which the magnetic components have important effect on the performance of VRM. In order to increase the power density and efficiency of VRM, the magnetic integration technology is applied to it [1-3]. However, each phase winding of the multi-phase magnetic integrated VRM has a self inductance, meanwhile, it can form coupled magnetic circuit with the other phase windings. Therefore, it is difficult to construct the model of VRM and the traditional linear control methods can not meet the demand of the performance [4]. A kind of 2-phase negative coupling magnetic integrated VRM is studied in this paper and its circuit model is constructed using linear system control theory, what's more, the corresponding nonlinear passivity-based control strategy is put forward to realize the equality of each phase current and to improve the dynamic performance of VRM.

2. Model Building of 2-phase Interleaving Magnetic Integrated VRM

The model of 2-phase interleaving negative coupled magnetic integrated VRM is shown in **Figure 1**. There are 4 operation modes in each switch cycle, and the corresponding equivalent circuits are shown in **Figure 2**.

Supposed that VRM operates in the mode of continuous current, and the 4 operating modes of VRM are defined as "Σ_1", "Σ_2", "Σ_3" and "Σ_4". The state variables are selected as $x=[x_1\ x_2\ x_3]^T$, where "x_1" and "x_3" are currents "i_1" and "i_2", "x_3" is voltage "u_c", "L_k" is leakage inductance, "k" is coupling coefficient, and "R" is the load resistance. The models of the 4 modes "Σ_1", "Σ_2", "Σ_3" and "Σ_4" are as follow:

$$\Sigma_1 : \dot{x} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_K} \\ 0 & 0 & \frac{-1}{L_K} \\ \frac{1}{RC} & \frac{1}{RC} & \frac{-1}{RC} \end{bmatrix} x + \frac{V_{in}}{L_K(1+2k)} \begin{bmatrix} 1+k \\ 0 \\ 0 \end{bmatrix} = A_{o1}x + b_{o1}$$

$$\Sigma_2 : \dot{x} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_K} \\ 0 & 0 & \frac{-1}{L_K} \\ \frac{1}{RC} & \frac{1}{RC} & \frac{-1}{RC} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = A_{o2}x + b_{o2}$$

$$\Sigma_3 : \dot{x} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_K} \\ 0 & 0 & \frac{-1}{L_K} \\ \frac{1}{RC} & \frac{1}{RC} & \frac{-1}{RC} \end{bmatrix} x + \frac{V_{in}}{L_K(1+2k)} \begin{bmatrix} 0 \\ 1+k \\ 0 \end{bmatrix} = A_{o3}x + b_{o3}$$

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$$\Sigma_4 : \dot{x} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_K} \\ 0 & 0 & \frac{-1}{L_K} \\ \frac{1}{RC} & \frac{1}{RC} & \frac{-1}{RC} \end{bmatrix} x + \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = A_{o4}x + b_{o4}$$

This is a typical switch affine linear system. Its operating process is switched in 4 modes. The convex scheme "Σ_{eq}" of 2-phase planar magnetic integrated VRM can be constructed as [4]:

$$\Sigma_{eq} : \dot{x} = \begin{bmatrix} 0 & 0 & \frac{-1}{L_K} \\ 0 & 0 & \frac{-1}{L_K} \\ \frac{1}{C} & \frac{1}{C} & \frac{-1}{RC} \end{bmatrix} x + \frac{V_{in}}{L_K(1+2k)} \begin{bmatrix} \lambda_1(1+k)+\lambda_3 k \\ \lambda_1 k + \lambda_3(1+k) \\ 0 \end{bmatrix} \quad (1)$$
$$= Ax + b$$

Equation (1) is the state equation model of 2-phase magnetic integrated VRM, and "λ_1" and "λ_3" are duty cycles of switch device "Q_{1H}" and "Q_{2H}", respectively.

3. Passivity-based Control Strategy of 2-phase Interleaving Planar Magnetic Integrated VRM

Supposed that the output state variables of VRM are "$x_d = [I_{L10}, I_{L20}, V_o]^T$", where "$I_{L10}$" and "$I_{L20}$" are steady state average currents and "V_o" is static state output voltage. The equilibrium state of the system defined by equation (1) is supposed as "x_d" and is translated to the origin of state space. The error vector is defined as:

$$x_e = x - x_d \quad (2)$$

Substituting equation (1) to (2), the error state equation of VRM model can be expressed as:

$$\dot{x}_e - Ax_e = b + Ax_d \quad (3)$$

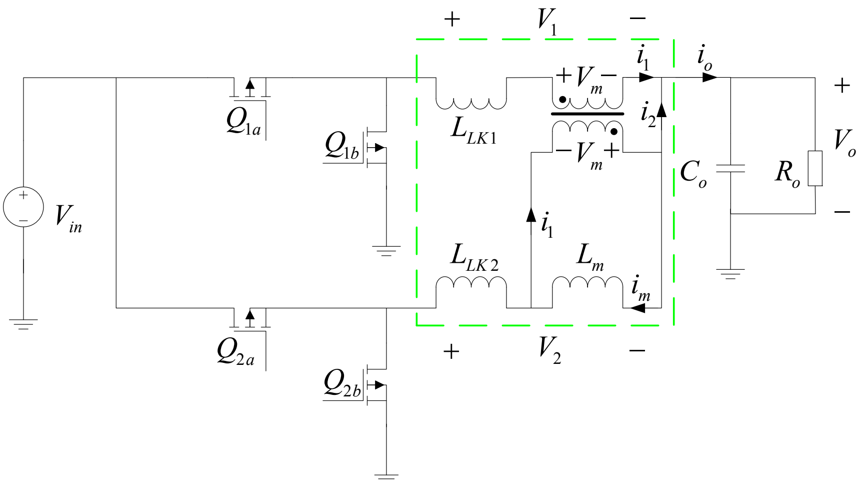

Figure 1. Equivalent circuit of two-phase negative coupled planar magnetic integrated VRM.

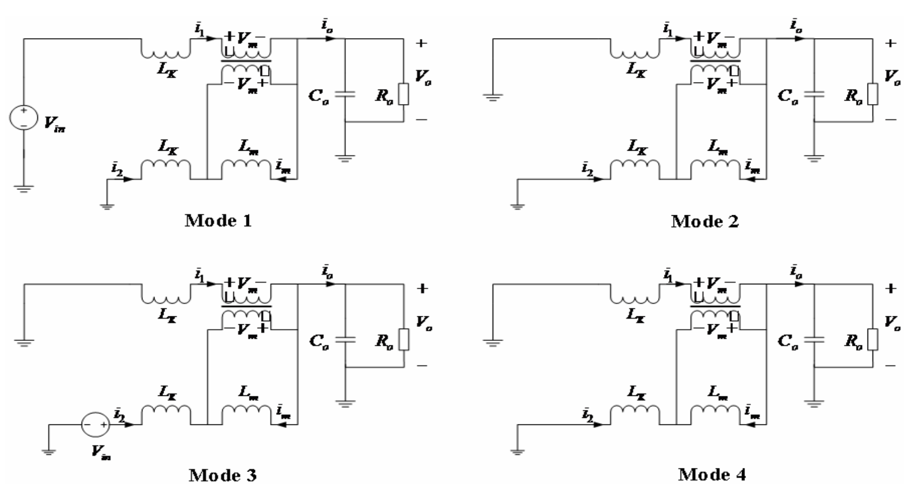

Figure 2. Four operating modes of 2-phase negative coupled planar magnetic integrated VRM.

Introduce a damping term "$\Re$"

$$\Re = \begin{pmatrix} -2R_1/L_K & 0 & 0 \\ 0 & -2R_1/L_K & 0 \\ 0 & 0 & 0 \end{pmatrix}, R_1 > 0 \quad (4)$$

and define a matrix "***E***" as:

$$E = \Re + A \quad (5)$$

Substituting equation (5) to (3), we have

$$\dot{x}_e - Ex_e = b + Ax_d - \Re x_e \quad (6)$$

Supposing that the right-hand side of equation (6) is always equal to zero, then:

$$\dot{x}_e - Ex_e = 0 \quad (7)$$

A Lyapunov energy function can be established as follow:

$$V(x_e) = \frac{1}{2} x_e^T P x_e \quad (8)$$

Selecting P as

$$P = \begin{pmatrix} L_K & 0 & 0 \\ 0 & L_K & 0 \\ 0 & 0 & R_1 C \end{pmatrix} > 0$$

then the Lyapunov energy function becomes

$$V(x_e) = \frac{1}{2} x_e^T P x_e = \frac{1}{2} L_K x_{e1}^2 + \frac{1}{2} L_K x_{e2}^2 + \frac{1}{2} R_1 C x_{e3}^2 > 0 \quad (9)$$

The derivative of Lyapunov energy function is:

$$\dot{V}(x_e) = -\frac{1}{2} x_e^T Q x_e < 0 \quad (10)$$

According to the asymptotic stability criterion of the control theory, the origin is asymptotically stable in the system defined by equation (8).That is to say, if and only if the right-hand side of equation (6) is constantly equal to zero, the error zero point is the system's intrinsic steady point, then

$$b + Ax_d - \Re x_e = 0 \quad (11)$$

Using equation (11), we can derive the expressions of "λ_1" and "λ_3" as follow:

$$\lambda_1 = \frac{V_o - 2R_1[x_{e1} + p(x_{e1} - x_{e2})]}{V_{in}} = \frac{V_o - 2R_1[x_1 - I_{L1} + p(x_1 - x_2)]}{V_{in}} \quad (12)$$

$$\lambda_3 = \frac{V_o - 2R_1[x_{e2} + p(x_{e2} - x_{e1})]}{V_{in}} = \frac{V_o - 2R_1[x_2 - I_{L2} + p(x_2 - x_1)]}{V_{in}} \quad (13)$$

Equation (12) and (13) are the passivity-based control strategy of 2-phase planar magnetic integrated VRM. With this strategy, if the input voltage "V_{in}", the output voltage "V_o" and the coupling coefficient "k" are known, the VRM can be controlled precisely to be on the steady operation point and is passive. This can guarantee that the VRM has a global stability. In addition, the dynamic response speed of the VRM can be regulated in certain range by adjusting the damping parameter "R_1".

4. Simulation Verifying

4.1. Steady Performance Simulation

The input voltage is "V_{in}=12 V", output voltage is "V_o=1.2 V", switch frequency is "f_s=200 kHz", output filter capacitance is "C=680μF", load resistance is "R_L=0.05 Ω", leakage inductance is "L_k=3 μH", mutual inductance is "L_m=3 μH", and the coupling coefficient is "k=0.5".

According to equation (12) and (13), the steady state performance of the 2-phase magnetic integrated VRM with passivity-based control is simulated and compared with that of 2-phase discrete inductor VRM, as shown in **Figure 3**. The blue curves (I_{f1}, I_{f2} and I_{fo}) are the current waveforms of discrete inductor VRM, and the green curves (I_{h1}, I_{h2} and I_{ho}) are the current waveforms of planar magnetic integrated VRM. It can be seen that the current ripples of magnetic integrated VRM are smaller than that of discrete inductor VRM, and this means that the negative coupling magnetic integrated VRM of passivity-based control has better steady state performance than that of the discrete inductor VRM.

4.2. Load Disturbance Simulation

The simulation waveforms shown in **Figure 4** are the simulation results of the process that the load resistance jumps from light load (R_{load}=0.05Ω) to full load (R_{load}= 0.025Ω) at the moment of 1ms and falls from full load to

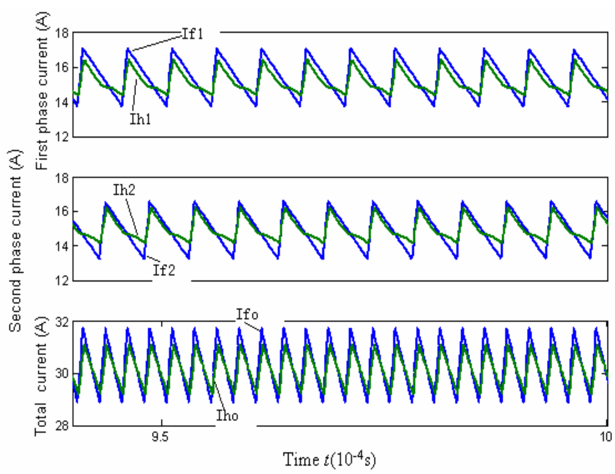

Figure 3. Steady state current waveforms of 2-phase VRM with passivity-based control strategy.

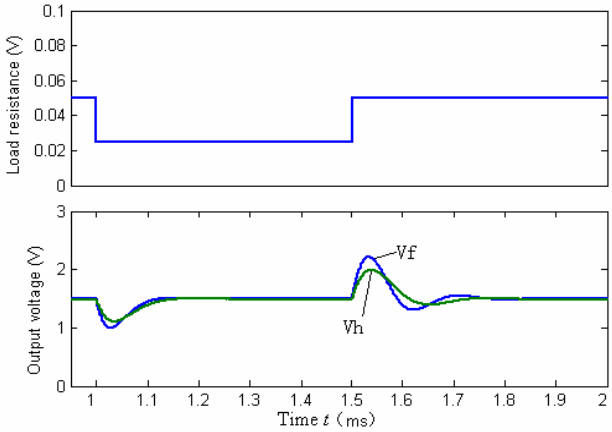

Figure 4. Dynamic response of output voltages of 2-phase VRM with passivity-based control strategy.

light load at the moment of 1.5 ms. The blue curve (V_f) is output voltage waveform of discrete inductor VRM under load disturbance, and the green curves (V_h) is output voltage waveform of magnetic integrated VRM under load disturbance. It can be seen that the drop value and over-modulation of dynamic output voltage of 2-phase magnetic integrated VRM are smaller than that of 2-phase discrete inductor VRM.

5. Conclusions

This paper brings passivity-based control method into 2-phase interleaving magnetic integrated VRM and puts forward a kind of passivity-based control strategy. The passivity-based control strategy is verified with MATLAB simulation. The simulation results prove that 2-phase interleaving magnetic integrated VRM with passivity-based control strategy can improve the steady state performance and the dynamic performance. Passivity-based control is a perfect control scheme for magnetic integrated VRM.

REFERENCES

[1] P. L. Wong, P. Xu, P. Yang and F. C. Lee, "Performance ImProvements of Interleaving VRMs with Coupling Inductors," *IEEE Tranctions on Power Electronics*, Vol. 16, No. 4, 2001.

[2] P. Xu, M. Ye and F. C. Lee, "Single Magnetic Push-pull forward Converter Featuring Built in Input Filter and Coupled-inductor Current Doubler for 48V VRM,"*IEEE Proceedings of APEC*, Vol. 2, No. 3, 2002, pp.843-849.

[3] L. P. Wong,Y. S. Lee and D. K. W. Cheng, "Simulation and Design of Integrated Magnetics for Power Converters," *IEEE Transactions on magnetics*, Vol. 39, No. 2, 2003, pp.1008-1018. doi:10.1109/TMAG.2003.808579

[4] P. Bolzern and W. Spinelli, "Quadratic Stabilization of A Switched Affine System about A Nonequilibrium Point," *Proceedings of the American Control Conference*, Vol. 25, No. 3, 2004, pp. 96-101.

