Sequence Based Control for Electro-thermal Management of Next Generation Integrated Power Systems

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Synopsis

An individual switching technique for semi-conductor components of power converters presents an individual electrical and thermal output performance. Therefore, understanding the switching patterns or sequence and their effect can significantly improve the overall performance of the power converters. In this paper, a sequence based control methodology for a power converter system to optimize its electrical and thermal performance will be presented, analysed, and discussed. The method includes modelling the converter system with respect to a sequence of switching events, defining and formulating the control objectives into a form of a cost function, and solving the cost function for the optimal electrical performance.

Keywords: Distributed control, data forecasting, and evidence theory

1. Introduction:

Next generation integrated power systems (NGIPS) will consist of a large number of power electronic converters [1]. These power converters while working with the generation and load devices will have both electrical and thermal coupling effects throughout the system. The optimal performance of these ship systems including stability, efficiency, and resiliency is desired. Therefore, the optimal performance requires the cooperation of thermal and electrical systems.

NGIPS have various events, which when operated will result in different sequences of events occurring in the system. The sequences of events will consequently affect the system performance. An example is that the sequence of switching states occurring in power converters will affect the system's power quality as well as the thermal characteristics of the system. Subsequently, variation in thermal characteristics will affect the cooling mechanism for the system. Then the cooling mechanism will require the power system to react. Generally, there are various sequences of events that can be projected to achieve system performances. Therefore, it is crucial to obtain the ideal sequence done by a sequence based control technique, which ensures the optimal electro-thermal performance of the system.

Conventional sequence based control (SBC) methods for power electronic systems usually have one prediction horizon, with insufficient information predicted. Existing multi-horizon approaches could be computationally expensive. Moreover, optimization of converter performance via changing switching states has mainly been single-dimensional in physical domains such as electrical and thermal. [2] presents an example to show that different switching sequences affect the thermal performance of a power converter, even though electrical performance is essentially the same.

In this paper, we will perform sequence based control for a power electronic based application, where the low-voltage ride through problem is taken into account as an example for demonstration of the proposed technique. The system consists of a single inverter. The control technique will regulate the converter systems so that they provide the maximum reactive power to an external AC power system when a predefined un-acceptable deviation in the system voltage occurs. Results for controlling the cascade converters in a real-time simulation environment will be presented to prove the effectiveness of the algorithm. In addition to the electrical performance, the thermal

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Authors' Biographies

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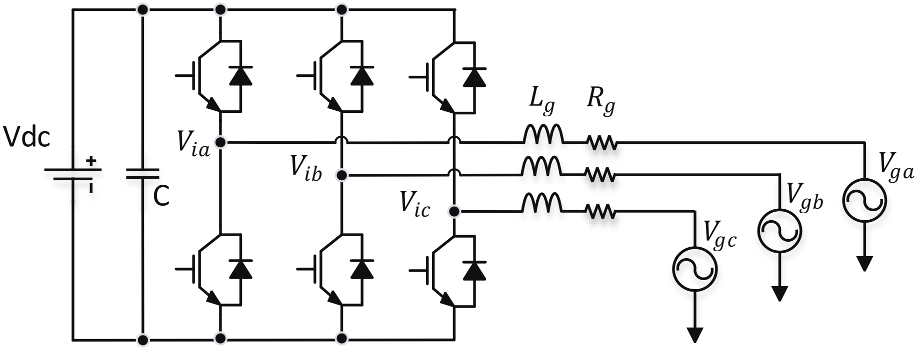

Fig. 1. Grid-connected Inverter system for low voltage ride through problem.

aspect, which couples with the electrical system will be described and formulated in detail. However, the thermal control results will not be discussed in the paper.

2. Sequence based control method

2.1. System description

The system of interest for control investigation and design is an inverter and is shown in Fig. 1, where L_g and R_g are the inductance and resistance components of the filter. The grid-connected inverter is to support the reactive power whenever there is a low-voltage sag event occurs in the distribution grid.

According to [3]-[5], the system model can be rewritten as

$$\begin{bmatrix} i_{gd}^{k+1} \\ i_{gq}^{k+1} \end{bmatrix} = \Phi \begin{bmatrix} i_{gd}^{k} \\ i_{gq}^{k} \end{bmatrix} + \Gamma_i \begin{bmatrix} V_{id}^{k} \\ V_{iq}^{k} \end{bmatrix} + \Gamma_g \begin{bmatrix} V_{gd}^{k} \\ V_{gq}^{k} \end{bmatrix}, \tag{1}$$

where

$$\Phi = e^{AT_s}, \Gamma_i = A^{-1}(\Phi - I_{2\times2})B_i, \Gamma_g = A^{-1}(\Phi - I_{2\times2})B_g, \tag{2}$$

and

$$A = \begin{bmatrix} \frac{-R_g}{L_g} & \omega_g \\ -\omega_g & \frac{-R_g}{L_g} \end{bmatrix}, B_i = \begin{bmatrix} \frac{1}{L_g} & 0 \\ 0 & \frac{1}{L_g} \end{bmatrix}; \; B_g = \begin{bmatrix} \frac{-1}{L_g} & 0 \\ 0 & \frac{-1}{L_g} \end{bmatrix}. \tag{3}$$

Please note that ω_g(rad/s) is the grid frequency. (1) is equivalent to

$$\begin{bmatrix} V_{id}^{k} \\ V_{iq}^{k} \end{bmatrix} = \Psi \begin{bmatrix} i_{gd}^{*,k+1} \\ i_{gq}^{*,k+1} \end{bmatrix} - \Upsilon_1 \begin{bmatrix} i_{gd}^{k} \\ i_{gq}^{k} \end{bmatrix} - \Upsilon_2 \begin{bmatrix} V_{gd}^{k} \\ V_{gq}^{k} \end{bmatrix}, \tag{4}$$

where

$$\Psi = \Gamma_i^{-1}, \Upsilon_1 = \Gamma_i^{-1}\Phi, \Upsilon_1 = \Gamma_i^{-1}\Gamma_g, \tag{5}$$

and $i_{gd}^{*,k+1}$ and $i_{gq}^{*,k+1}$ are reference currents.

2.2. Methodology

The idea of SBC is shown in Fig. 2, where N_p is the prediction horizon, S is the number of switching states in each sequence. Therefore, the total number of sequences is S^{N_p}. Each sequence represents a specific system performance. The optimal sequence of switching will present the best electrical and thermal performance. The objectives of the research can be turned into a general multi-objective cost function of the systems of power converters, which is formulated as follows:

$$\begin{gathered} \min J_{ET} = w_E J_E(s) + w_T J_T(s) \\ \text{s.t. } s \in S, \end{gathered} \tag{6}$$

where s is the switching state of a converter, S is the feasible set of s, w_E is the electrical weight constant, w_T is the thermal weight constant, $J_E(s)$ is the cost function related to the electrical performance, and $J_T(s)$ is the cost function related to the thermal performance.

2.2.1. Electrical control

The objective of the electrical control is to satisfy the current references $i_{gd}^{*,k+1}$ and $i_{gq}^{*,k+1}$ so that the desired power injected to the grid will be satisfied. The cost function is formulated in a quadratic form as described in [3].

$$J_g^k = \left[i_{gd}^{k+1} - i_{gd}^{*,k+1}\right]^2 + \left[i_{gq}^{k+1} - i_{gq}^{*,k+1}\right]^2 \tag{7}$$

or

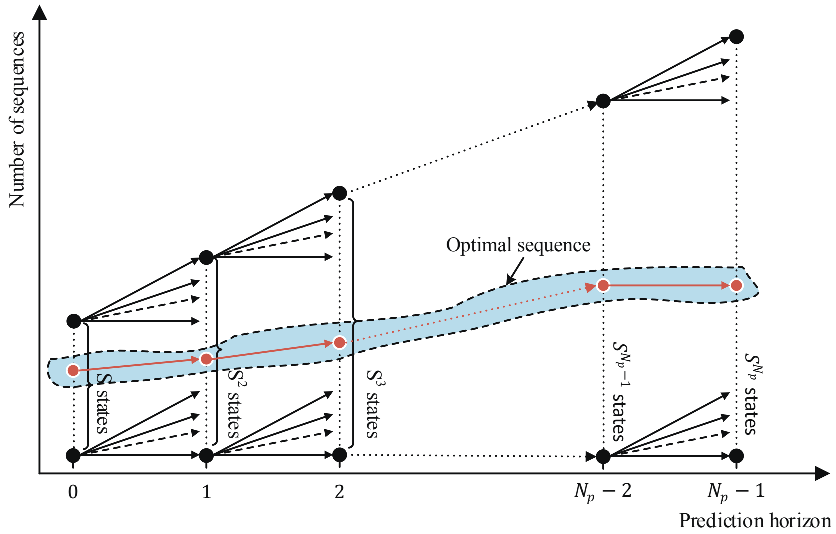

Fig. 2 SBC for the system with feasible set of states and N_p prediction step.

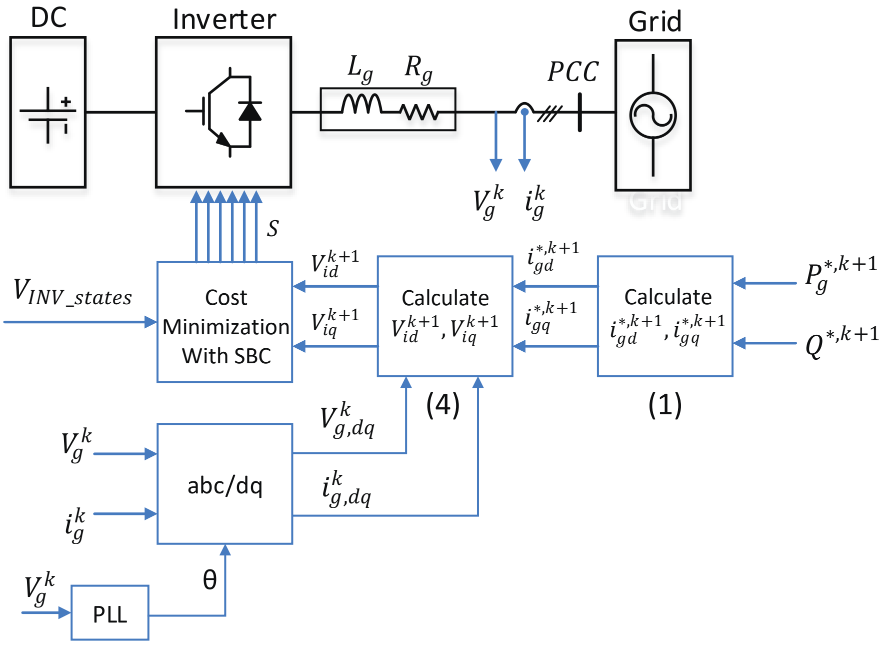

Fig. 3 Grid Connected Control System.

$$J_g^k = \left[V_{id}^k - V_{INV\_States,d}\right]^2 + \left[V_{iq}^k - V_{INV\_States,q}\right]^2 \tag{8}$$

where

$$V_{INV\_States} = \begin{bmatrix} V_{INV\_States,d} \\ V_{INV\_States,q} \end{bmatrix} = \left[T_{dq}^{-1}\right][V_{ix}], \tag{9}$$

and

$$\left[T_{dq}^{-1}\right] = \begin{bmatrix} \cos(\theta) & \cos(\theta + 2\pi/3) & \cos(\theta - 2\pi/3) \\ \sin(\theta) & \sin(\theta + 2\pi/3) & \sin(\theta - 2\pi/3) \end{bmatrix}. \tag{10}$$

2.2.2. *Thermal control*

Following procedure is to derive the thermal characteristics for future proposed control method; however, the solution and results regarding the thermal characteristics will not be discussed further in the paper.

To formulate the thermal objective $J_T(s)$, we start from the average switching power loss of a switching device due to switching, which can be expressed as

$$P_s(t) = \frac{1}{2} V_d I_0 f_s (t_{s,on} + t_{s,off}), \tag{11}$$

where V_d is the open-circuit voltage of the switching device during the off-switching state, I_0 is the conducting current through the switching device during the on-switching state, f_s is the switching frequency, $t_{s,on}$ is the transient time from the off-state to the on-state, and $t_{s,off}$ is the transient time from the on-state to the off-state.

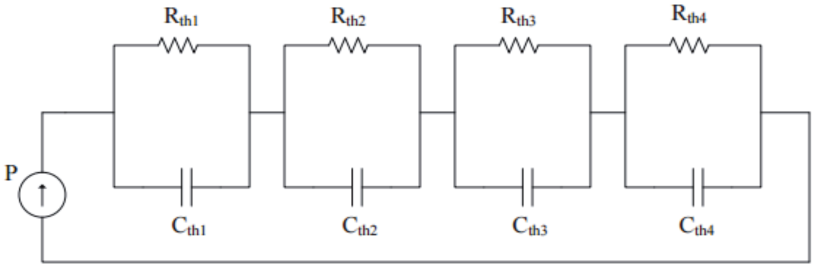

Fig. 4 Foster network for device thermal characteristic.

To describe the thermal characteristic of a switching device, we utilize the Forster network model (Fig. 4). The junction thermal impedance Z of the switching device for the heat-dissipation is the function of duty cycle and pulse length as [2]:

$$Z_{JC}(t) = \sum_{i=0}^{n} R_{thi} \frac{\left(1 - e^{-\tau_p/\tau_i}\right)}{1 - e^{-\tau_p/\tau_i} D}, \tag{12}$$

where R_{th} is the thermal resistance of the device, τ_p is duration of pulse applied, $\tau_i = R_{thi} C_{thi}$ is the Foster network time of the device, D is the duty cycle. This thermal impedance and power dissipated (11) results in the following operational temperature of the switching device as

$$T_{JC}(t) = P_s(t) Z_{JC}(t) + T_c(t), \tag{13}$$

where $T_c(t)$ is a known base plate temperature. The cooling mechanism will depend on the junction temperature.

As seen, the junction temperature T_{JC} of a switching device depends on the switching frequency f_s, pulse length τ_p, and duty cycle D. On the other hand, the temperature T_{JC} is a function of the switching sequence $T_{JC}(s)$. Therefore, it is required to minimize this temperature in order to reduce the weight, size, and cost of the system. The average temperature of a converter system with N_s switching devices can be written as

$$g(s) = T_{JC,avg}(s) = \frac{1}{N_s} \sum_{j=1}^{N_s} T_{JC,j}(s). \tag{14}$$

Therefore, the objective function describing the thermal characteristic of a system with n converters can be formulated as

$$J_T(s) = \sum_{i=1}^{n} w_{Ti}\, g_i(s), \tag{15}$$

where w_{Ti} is the weight factor related to the converter i.

As a result, the solution of the electro-thermal cost formulation (6) of the proposed SBC will be the optimal switching sequence applied in each converter of the ship power systems.

3. Simulation results

In this section, the simulation was performed for the electrical performance only. The simulation was conducted in PLECS blockset and MATLAB/Simulink, where the physical system was simulated in PLECS and control system was performed in Simulink. Information regarding the system is shown in Table 1. The test case is as follows. Before 40 ms, the inverter system did not inject power to the grid. From 4 40 ms to 150 ms, the inverter generated maximum active power at 4.8 kW to the grid with no reactive power injection. The voltage sag occurred at 150 ms and extended to 300 ms. After 300 ms, the inverter generated maximum power at 4.8 kW to the grid and did not generate reactive power to the grid. The results for 1 phase voltage (V_a) and current (i_a), and active power (P_g) and reactive power Q are shown in Fig. 5.

Table 1. Simulation system parameters.

Symbol	Quantity	Value
$V_{g,ll}$	Grid side line to line voltage	208 V
ω_g	Grid frequency	60 Hz
V_{dc}	DC power supply voltage	400 V
P_{INV}	Inverter nominal power	4.8 kW
T_s	Sampling time	20 µs
h	Prediction horizon	1

4. Discussion

Before 40 ms, there is no active and reactive power generated to the grid. Therefore, the current injection $i_a = 0\,A$. From 40 ms to 150 ms, the grid required that inverter to generated a maximum power at $P_g = 4.8$ kW. The SBC commanded the optimal switching sequence for the power tracking control. From 150 ms to 190 ms, the voltage sag occurred emulating a fault in the excitation system of the power generator, which decreased the voltage level by 50 % causes the inverter to trim down the active power to 0 kW to maximize the reactive power by maximizing the magnitude of the current injection i_a and shifted it 90^0 lagging to the voltage V_a. From 190 ms to 300 ms, the grid voltage recovered to the nominal value. As the voltage increased the reactive power required decreased and active power increased. As the voltage was completely recovered to the nominal value there was no need to inject the reactive power and the active power was again maximized, where the current i_a was in-phase with the voltage V_a.

Therefore, the SBC algorithm effectively controls the switching sequence of the semiconductor devices in the inverter to guarantee the optimal reactive power support to the grid under the low voltage conditions. In this paper, the thermal performance has not been discussed. Future papers will discuss the electrical and thermal performance of the technique in comparison with traditional switching techniques such as PWM and Hysteresis control.

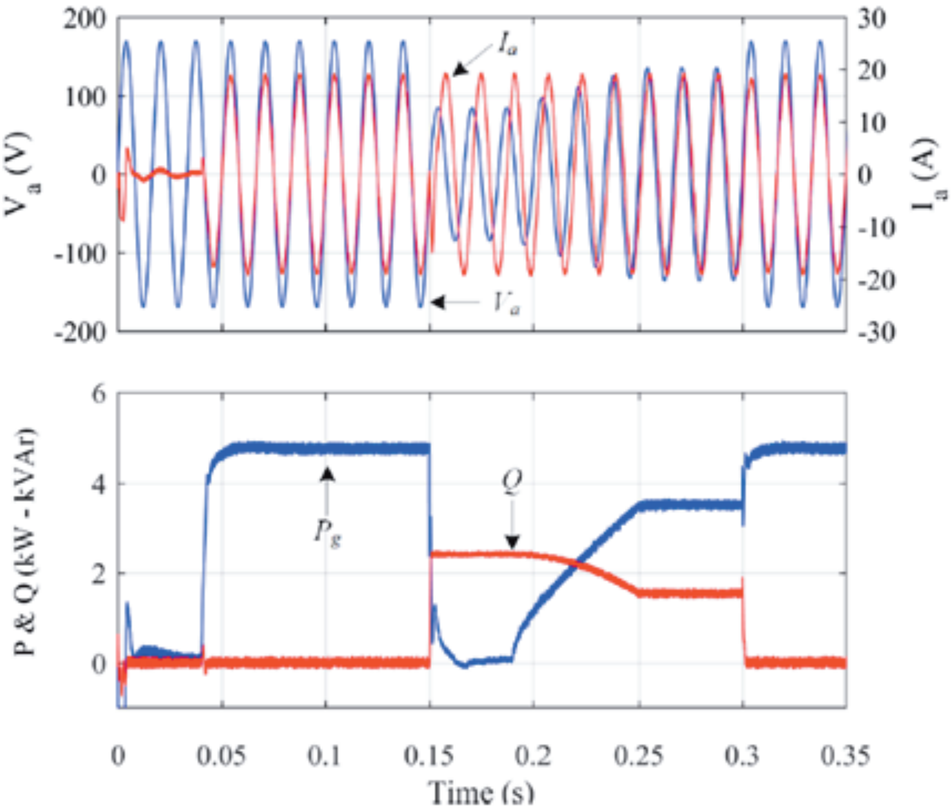

Fig. 5 Low voltage ride through simulation.

5. Conclusion

In this paper, the SBC control method was presented as a potential candidate to provide the optimal performance of power converter systems. This can effectively reduce the size and the cost of NGIPS. Results for a case study of a grid-connected inverter system for reactive power support in the presence of low-voltage on the power grid demonstrated the effectiveness of the proposed method in the electrical performance. The future work will present the multi-objective optimization algorithm for simultaneously optimizing the thermal and electrical performance of the power converter systems.

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