AN APPLICATION OF SPLIT-PI CONVERTER TO MICROGRID WITH DC-MOTOR LOAD

ỨNG DỤNG BỘ BIẾN ĐỔI SPLIT-PI TRONG LƯỚI ĐIỆN SIÊU NHỎ CÓ PHỤ TẢI ĐỘNG CƠ ĐIỆN MỘT CHIỀU

Vu Hoang Giang, Nguyen Phuc Huy

Electric Power University

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Abstract:

This paper proposes an application of Split-Pi converter to the integration of various elements in a single smart node of microgrid. A smart node is created to receive the power from the sources, which includes a photovoltaic system (PV) and a common DC bus, and supply to DC loads, including DC motor. The stability of converter DC-link voltage, the wide range and robustness of speed regulation of the DC motor are the main requirements in this application. Two controllers are introduced to regulate the DC-link voltage and the DC-motor speed. Each controller is established with an outer loop of proportional integral (PI) regulator and an inner loop of sliding-mode current regulator. The sliding-mode regulators are used for the inner control loop regulators since they offer several benefits such as high stability and robustness of the voltage and speed responses. The smart node with converter DC-link can be also used for the development of mesh network for the microgrid. Computer simulation confirms the effectiveness of proposed configuration.

Key words:

DC motor, microgrid, Proportional-Integral control, Sliding-mode control, Split-Pi converter.

Tóm tắt:

Bài báo đề xuất một ứng dụng của bộ biến đổi Split-Pi trong tích hợp nhiều phần tử khác nhau trong một nút thông minh của lưới điện siêu nhỏ. Nút thông minh được tạo ra để tiếp nhận công suất từ nhiều nguồn khác nhau, bao gồm một hệ thống pin mặt trời, thanh góp chính một chiều, cung cấp cho tải một chiều trong đó có động cơ điện một chiều. Yêu cầu chính của ứng dụng này là cần đảm bảo sự ổn định điện áp của thanh góp chính một chiều, phạm vi điều chỉnh rộng và đáp ứng điều chỉnh nhanh của bộ điều khiển tốc độ động cơ. Hai bộ điều khiển được sử dụng để điều khiển điện áp của thanh góp chính một chiều và tốc độ của động cơ. Mỗi bộ điều khiển được tạo bởi vòng điều chỉnh ngoài kiểu tích phân-tỷ lệ và vòng điều chỉnh dòng điện bên trong kiểu trượt. Các bộ điều chỉnh kiểu trượt được sử dụng cho vòng trong vì có nhiều ưu điểm như đáp ứng điện áp và tốc độ ổn định cao và nhanh. Nút thông minh với kết nối một chiều cũng có thể được sử dụng trong lưới điện mạch vòng của lưới điện siêu nhỏ. Mô phỏng trên máy tính xác nhận tính hiệu quả của cấu hình đã đề xuất.

Từ khóa:

Động cơ điện một chiều, lưới điện siêu nhỏ, điều khiển kiểu tích phân - tỷ lệ, điều khiển trượt, bộ biến đổi Split-Pi.

1. INTRODUCTION

Along with the rapid development of renewable energy sources such as wind power and photovoltaic (PV) systems, the structure of microgrid is correspondingly evolved in order to be appropriate for local supplying power systems. The microgrid is commonly divided into AC microgrid, DC microgrid and hybrid AC-DC microgrid. The DC microgrid offers several advantages including the suitability with the sources like PV systems, which are instinctively DC sources. Furthermore, DC loads such as LED lighting, DC motor, electric vehicles, etc., are replacing lower efficiency AC loads [1]. According to [2], 90% of the traditional house appliances are able to be substituted by DC ones. In the AC network, the connection of DC loads to the AC section requires multiple stages of DC-AC and AC-DC converters that causes high power losses in the distribution system. Inversely, the DC microgrid offers several superiorities including: lower losses, higher efficiency, reliability and stability.

Playing the role of power transformers in AC grid, various topologies of DC-DC converters have been used in DC microgrids [3]. As a recently potential choice, DC-DC Split-Pi converter has been increasingly applied to the microgrid due to the capability of bidirectional control of power flow [4], [5], [6]. Moreover, it can be used as a smart node in the DC network [7]. It has been used in various applications including the electric vehicles, DC motor control, battery management and energy conversion [8]. For the microgrid, the converter is expected to contribute efficiently and reliably to the integration of renewable energy sources, battery storage systems and various types of loads.

In this paper, we propose a configuration of DC power supply system using Split-Pi converter with two decoupled controllers for regulating the DC-link voltage and the DC motor speed. It will be shown that the utilization of Split-Pi converter with selected control system permits building a node with stable voltage under the variation of power fed by the PV system due to the intermittence of solar irradiation and the change of DC load demand. In addition, the constraint of keeping the speed response of the DC motor is guaranteed. The DC motor is chosen to investigate since it can still be found in extensive application of steel plants, paper and textile mills, printing presses, cranes and winches. Furthermore, the DC motor has several advantages including high starting torque, wide range of speed control, quick starting, stopping, reversing and accelerating [9].

The remainder of paper is organised as follows. Section 2 introduces the configuration of DC power supply system and the controllers. Simulation results are then presented in Section 3. Finally, some conclusions are given in Section 4.

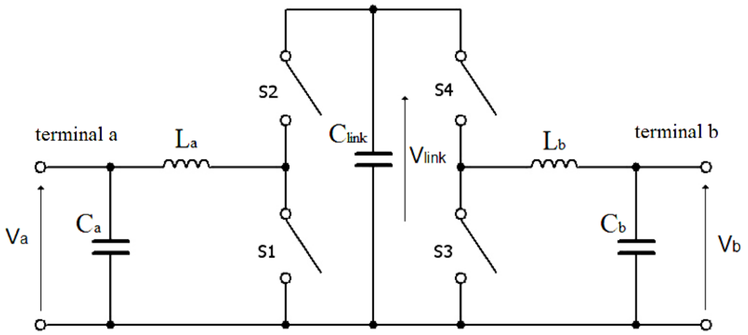

Fig. 1. Principle diagram of a Spli-Pi converter [10]

2. DC MOTOR POWER SUPPLY SYSTEM

2.1. Structure of microgrid

The DC-link of the Split-Pi converter is used to create a special node in the DC microgrid.

Split-pi is a DC-DC converter, illustrated in Fig. 1.

The converter is mainly composed of 4 power electronic switches: S_1, S_2 at terminal a; S_3, S_4 (terminal b); and a DC-link capacitor in the middle.

In the structure, Split-Pi converter is a type of buck-boost converter, which is commonly used in the DC-DC conversion applications [11]. This converter allows regulating the power at both terminals of a and b by controlling the duty of the four switches with pulse width modulation (PWM) at high frequency.

The Split-Pi converter is connected to the following elements, as shown in Fig. 2.

- The DC common bus (E): this is the common bus of the grid, which is commonly at the DC side of a DC/AC converter connected to the main AC grid. The bus voltage is controlled by the converter controller. The bus is connected to one port of the Split-Pi converter.
- PV is connected to the DC-link via a DC-DC converter [12], which is MPPT controlled to extract maximum power from the Sun;
- DC load, whose consuming power can be changed, is supplied from the DC-link. To assure the operation of the load, as afore mentioned, the DC-link voltage needs to be remained around its nominal value;
- A separately connected DC motor is connected to the other port of the converter. Mathematical model of the motor is given by [13]:

$$\begin{cases} v_f = R_f(1+p\tau_f)i_f \\ v_a = R_a(1+p\tau_a)i_a + k_v\omega_r \\ T_e - T_L = (B_m + Jp)\omega_r \end{cases} \qquad (1)$$

where: v_f and i_f are the field voltage and current, respectively; v_a and i_a are armature voltage and current, respectively; ω_r is the motor speed; T_e is the electromagnetic torque, $T_e = k_v i_a$; T_L is the load torque; p denotes d/dt; $\tau_f = L_f/R_f$, $\tau_a = L_a/R_a$, with R_f, L_f, R_a, L_a, k_v, B_m, and J are the parameters of DC motor, given in the appendix.

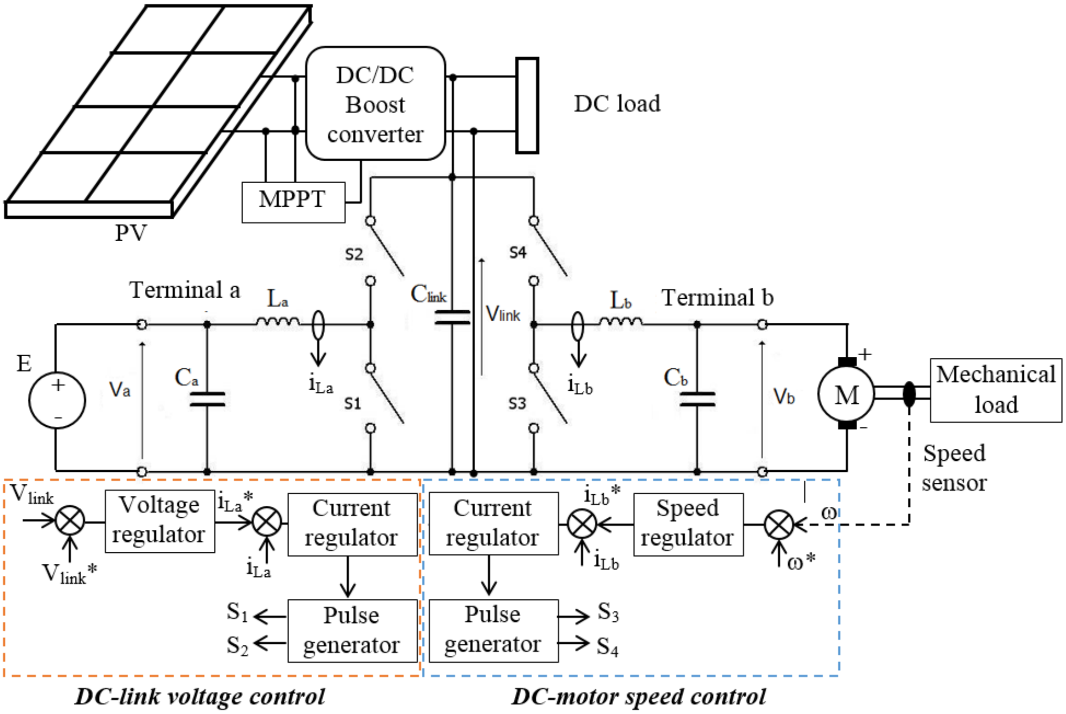

Fig. 2. Configuration of proposed power supply systems

2.2. Control system

The control system is composed of two controllers for regulating the DC-link voltage and the motor speed. A detailed description of these controllers will be shown as follows.

The first controller is responsible for holding the DC-link voltage in a permitted deviation from the nominal value. It includes an inner current control loop and an outer control loop for the DC-link voltage. The voltage control loop uses PI regulator whereas sliding-mode regulator is applied in current control loop.

In this study, the half of converter with terminal "a" operates in boost mode that the model of boost converter can be utilized to design the regulator.

Since the dynamic of current control loop is much greater than that of the voltage control loop, the closed loop system of converter proposed in [14] can be applied. Accordingly, the transfer function of the closed loop system is written by:

$$\frac{V_{link}}{E} = \frac{\frac{R}{L_a} s}{s^2 + \frac{\alpha R K_{pv}}{L_a} s + \frac{\alpha R K_{pi}}{L_a}} \qquad (2)$$

where L_a is the parameter of the converter, R is considered as a load at the DC-link, K_{pv} and K_{iv} are the parameters of the PI voltage regulator, $\alpha = 1/(1 - D)$ with D is the duty cycle.

Following that, the parameters of the PI regulator can be calculated by using different methods such as the Ziegler-Nichols method combined with loop shaping method [14]. In our study, these parameters are computed by equating the coefficients of the closed loop characteristic polynomial to those of a desired characteristic polynomial $p_d(s)$ of the form:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0 \quad (3)$$

with ζ is the damping factor and ω_n is the undamped natural frequency. Hence, we obtain: $K_{pv} = 0.5$; $K_{iv} = 10$.

In addition, for the current regulator, the following control strategy can be applied [15]:

$$u = 0.5.[1 + \mathrm{sign}(i_{La} - i_{La}^*)] \quad (4)$$

where i_{La}^* is the reference, which is the output of the voltage regulator. The sliding-mode technique is selected since it is naturally suited for the regulation of switched controlled systems. It allows to reduce the system order and the controller is less sensitive to the variation of system parameters.

The speed of DC motor is regulated by the second controller, which is composed of an inner current control loop and an outer speed control loop. The design of current regulator is similar to that of DC-link voltage controller. Differently, the speed regulator is a PI type controlling the speed to obtain a minimum steady-state error and transient duration. Its design is in the following.

In the condition of constant excitation, the electromagnetic torque is directly proportional to the armature current. Moreover, the inductor current at the terminal "b" i_{Lb} of the converter can be calculated by:

$$i_{Lb} = i_a + i_{Cb} \quad (5)$$

where i_{Cb} the capacitor current at terminal "b", in steady state $i_{Cb} = 0$. It means that the speed can be controlled via the inductor current i_{Lb}; and the capacitor current i_{Cb} plays as a disturbance in the control loop.

From the third equation of (1), a first-order transfer function between the armature current i_a and the motor speed ω_r can be derived. Following this, the parameters of the speed PI regulator that operates in the closed loop with the feedback of speed can be determined on the basis of a second-order characteristic equation. By equating this equation to a desired one, given in traditional form (3), we obtain the parameters of the speed regulator as: $K_{pw} = 3$; $K_{iw} = 10$.

3. SIMULATION RESULTS

In order to illustrate the performance of the controller, simulation of proposed configuration is developed in following conditions:

- The voltage of DC common bus E is 400 V;

- The nominal voltage of DC-link V_{link} is 500 V;
- The model of single Diode [16] is applied;
- The parameter of Sunpower SPR-305-WHT-U (305W) solar panel is used [17];
- The controller uses parameters in Section 2.

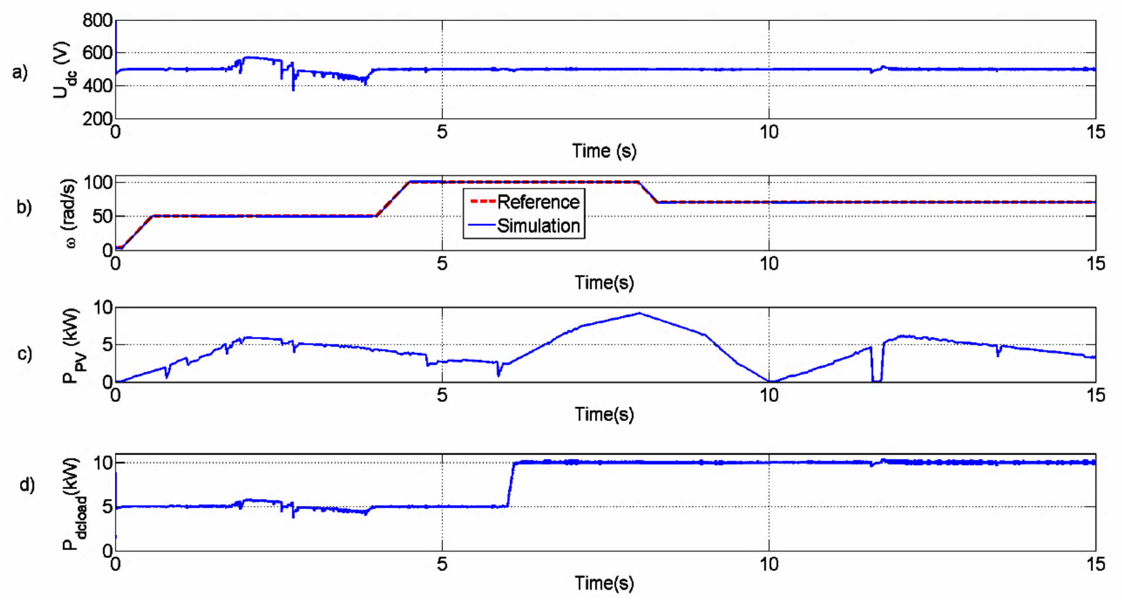

Fig. 3. A) DC link voltage, b) DC motor speed, c) PV power, d) DC load power

Fig. 3 presents main simulation results of system shown in Fig. 2 in the period of 15 s. As can be seen the DC-link voltage is remained fair stability around the nominal value although there is a disturbance in the duration (2-4) s. Meanwhile, the DC motor speed is robust controlled under the variation of the PV power variation, Fig.3, c or the change of DC load, Fig.3, d. It is noted that the speed is regulated in a wide operation range from stationary state to the nominal speed. It must be underlined that the simulation condition is quite exaggerated since the PV power rate of change is much slower in reality. The obtained results demonstrate the effectiveness of the proposed configuration and the highly satisfactory performance of the designed controllers.

4. CONCLUSION

An application of Split-Pi converter has been shown for microgrid, which include PV system and a dynamic load of DC motor. The control of the converter has been developed and successfully validated in simulation. As future works, the proposed structure will be extended by connecting to other components such as the energy storage system. In addition, the droop control will be developed in the scenario that the DC motor is fed by multiple sources.

5. APPENDIX

Parameters of DC motor 5 HP 240 V

1750 rpm, $U_f = 300$ V, $R_a = 2.581\ \Omega$, $L_a = 0.028$ H, $k_v = 1.011$ Vs/rad, $R_f = 281.3\ \Omega$, $L_f = 156$ H, $J = 0.02215$ kgm^2/s^2, $B_m = 0.002953$ N.m.

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Biography:

Vu Hoang Giang received the B.S degree and the M.S. degree in Electrical Engineering from Hanoi University of Science and Technology, Vietnam in 2002 and 2005, respectively, and then PhD degree in Electrical Engineering at University of Claude Bernard Lyon 1, Lyon, France in 2014. He is current full-time lecturer at Electric Power University in Vietnam.

His research interests include condition monitoring, state and parameter estimation of of electrical machines and power converters, control and protection of microgrids.

Nguyen Phuc Huy received his B.S and M.S degree in Electrical Engineering from Hanoi University of Science and Technology (HUST), Viet Nam in 2003 and 2010 respectively, and the PhD degree in the Electric Power System and Its Automation at North China Electric Power University (NCEPU), Beijing, China in 2015.

His research interests include Power Quality, Application of Power Electronic in Power System, and Power System Reliability.