분산 그리드내 PV통합용 그리드 포밍 반도체 변압기

바바요미 올루레케, 박기범
한국과학기술원

Grid-forming Solid-State Transformer for Solar PV Integration into Distribution Grids

Oluleke Babayomi, Ki-Bum Park
Korea Advanced Institute of Science and Technology

ABSTRACT

This paper introduces a comprehensive control scheme for the integration of renewable energy sources (solar PV) into the distribution grid by grid-forming solid-state transformers (SST). The proposed method combines nonlinear robust control of the SST with inertia emulation from the virtual synchronous generator (VSG) for high-performance active-power-frequency and reactive-power-voltage regulation. The isolated dc/dc dual-active-bridge in the SST is controlled using active disturbance rejection control (ADRC), while the inverter stage is controlled by VSG-droop-based model predictive control. The superior robustness and disturbance-rejection capabilities, along with fast dynamic response to both load changes and variations in solar irradiance, are demonstrated with simulation results.

1. Introduction

The integration of renewable energy sources facilitates the decarbonization of the electrical power grid. In particular, the output of solar PV farms can be integrated to the distribution grid through the high-efficiency solid-state transformer (SST)[1]. The SST can transform the medium voltage dc (MVdc) from the solar PV farm into low voltage ac (LVac) (see Fig. 1).

Nonetheless, when the SST becomes meshed in the conventional grid, its control becomes more challenging as its architecture in the grid changes from radial to meshed, depending on the flexible needs of the grid. In the radial structure, when circuit breaker NOP is open, SST operates as a grid-forming (GFM) converter; but when NOP is closed, the SST needs to operate in grid-following (GFL) mode in the meshed network. Conventional solutions apply linear control to the control of the SST stages comprising dual-active-bridge (DAB) isolated dc/dc stage and ac/dc inverter (Fig. 2) output stage [2]. Nonetheless, as several stages are coupled, and connected to the grid, the overall control scheme can become more complex. Also, intermittent solar PV input variations and load disturbances are not effectively suppressed. Therefore, this paper presents nonlinear robust control of the DAB and inverter stages using active disturbance rejection control (ADRC) and the virtual synchronous generator (VSG)-model predictive control, respectively. Also, the paper proposes a new smooth transition control between GFM and GFL modes of operation with minimal grid voltage overshoots or distortions.

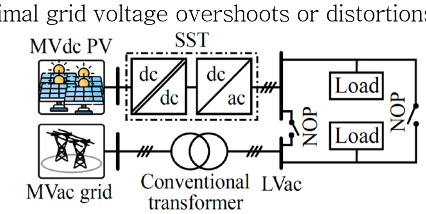

그림1 태양광 PV를 배전망에 통합하기 위한 반도체 변압기.

Fig.1 Solid-State Transformer for Solar PV Integration into Distribution Grids

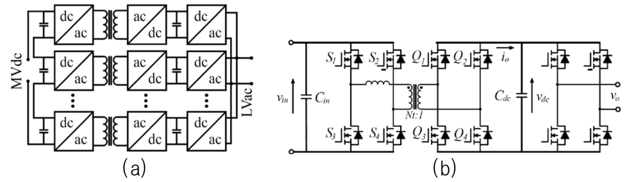

그림2 SST 구성. (a) 다중 병렬 컨버터. (b) 단일 종단 간 SST 하위 모듈.

Fig.2 SST configuration. (a) Multiple strings of converters. (b) Single end-to-end SST submodule.

2. Proposed Methodology

The proposed control scheme is shown in Fig. 3: it applies ADRC to the DAB control, and VSG-MPC (with seamless change between GFM and GFL modes) to the inverter.

2.1 DAB Controller

ADRC improves robust control by decreasing the dependence of the controller on the parameters of passive elements by the model-free equation:

$$\frac{dv_o}{dt} = \psi + \alpha\phi \qquad (1)$$

where α is the control input gain, ψ is the lumped disturbance. $\psi = -\frac{v_o}{R_L C_o}$, and α is a unitless scalar with an initial value of $\alpha_o = \frac{N_t V_{in}(1-4\bar{\phi})}{f_s L C_o}$. ψ is used to account for all system disturbances and unmodeled dynamics. The feedback controller requires estimates of v_o and ϕ, which are represented as $\hat{v_o}$ and $\hat{\phi}$, respectively. This can be done with the linear extended state observer (LESO). The resulting controller is shown in Fig. 4; transfer functions are defined:

$$G_{\psi\phi}(s) = \frac{\hat{\psi}(s)}{\hat{\phi}(s)} = -\frac{-\omega_o^2\alpha}{s^2+2\zeta\omega_o s+\omega_o^2} \qquad (2)$$

$$G_{\psi v}(s) = \frac{\hat{\psi}(s)}{\hat{v}_o(s)} = \frac{-\omega_o^2 s}{s^2+2\zeta\omega_o s+\omega_o^2} \qquad (3)$$

where ω_o is the LESO bandwidth.

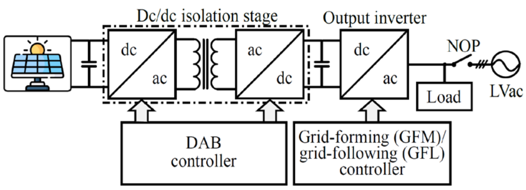

그림3 제안하는 SST 제어 방식

Fig.3 Proposed control scheme for the SST

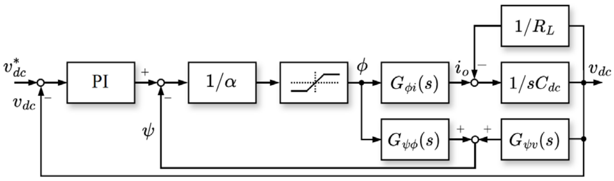

그림4 제안하는 DAB 컨버터의 ADRC 제어 방식

Fig.4 Proposed ADRC control scheme for the DAB converter.

2.2 Output Inverter Controller

The SST's inverter operates in GFM mode when NOP is open, and in GFL mode when NOP is closed. The overall control scheme is shown in Fig. 5, where the VSG provides superior GFM performance.

2.2.1 Grid-forming (GFM) operation mode

The objective in grid-forming mode is to ensure high-quality voltage and current control at the LV AC bus. Here, predictive control is achieved by minimizing the cost function

$$J_l = \left(\hat{v}_{l\alpha\beta}(k+1) - v_{l\alpha\beta}^*\right)^2 + \wp\left(\hat{\imath}_{l\alpha\beta}(k+1) - i_{l\alpha\beta}^*\right)^2, \quad (4)$$

where $r_{\alpha\beta} = [r_\alpha, r_\beta]^T$, $v_l^*$is the output voltage reference, $\wp$ is the weighting factor that determines the control priority between current and voltage control, and $i_{o\alpha\beta}^*$ is the output current reference computed from

$$i_{l\alpha\beta}^* = (C_l\omega_g v_{l\beta}^* + i_{o\alpha}) + j(i_{o\beta} - C_l\omega_g v_{l\alpha}^*). \quad (5)$$

2.2.2 Grid-following (GFL) operation mode

In GFL mode, the grid voltage $v_{g\alpha\beta} = [v_{g\alpha}, v_{g\beta}]^T$ provides the voltage reference ($v_{l\alpha\beta}^* = v_{g\alpha\beta}$). The conventional power control for grid-connected operation would not give a seamless transition from GFM to GFL. Therefore, the new current reference terms are derived from instantaneous power expressions:

$$\begin{cases} i_{l\alpha}^* = \frac{2}{3}\left(\frac{p_l^* v_{l\alpha}^* + q_l^* v_{l\beta}^*}{{v_{l\alpha}^*}^2 + {v_{l\beta}^*}^2}\right) \\ i_{l\beta}^* = \frac{2}{3}\left(\frac{p_l^* v_{l\beta}^* - q_l^* v_{l\alpha}^*}{{v_{l\alpha}^*}^2 + {v_{l\beta}^*}^2}\right) \end{cases} \quad (6)$$

where $v_{l\alpha\beta}^* = v_{g\alpha\beta} = [v_{g\alpha}, v_{g\beta}]^T$; $p_l^*$and q_l^* are the active and reactive power references respectively. The same cost function (4) is used to optimize the switching vectors selected for the power converters.

3. Simulation Verification

PLECS software simulation results for the system (Fig. 3), with controllers in Figs. 4 and 5 are shown in Figs. 6 to 8.

Since solar PV farms have outputs that vary with the daily insolation, the impact of variable input voltage is shown in Fig. 6. The proposed ADRC controller for the DAB converter has two advantages over the conventional linear control. First, are

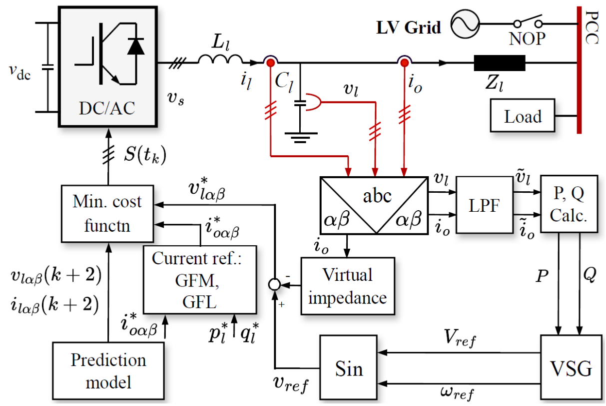

그림5 제안하는 출력 인버터에 대한 GFM/GFL 제어 방식

Fig.5 Proposed grid-forming/grid-following control scheme for the output inverter stage.

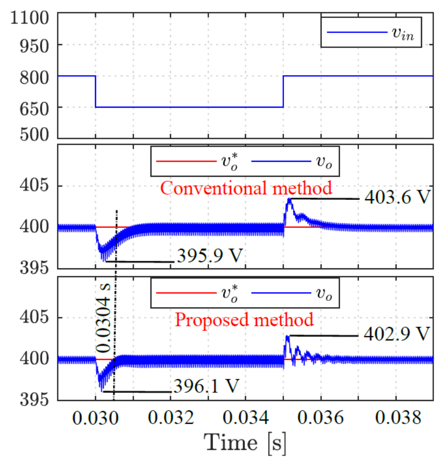

그림6 DAB 컨버터 제어에 대한 시뮬레이션 결과.

Fig.6 Simulation results for DAB converter control.

lower overshoots during input voltage changes. Second, it recovers faster from external disturbances: a settling time that is 60% smaller than the conventional method.

In addition, the proposed VSG-MPC results shown in Fig. 8, demonstrate superior capabilities over the conventional controller (Fig. 7). The seamless transition between GFM to GFL modes has eliminated current and voltage overshoots. Meanwhile, the GFL voltage quality is better than with the conventional method.

표 1 시스템 매개변수의 값.

Table 1 Values of the system parameters

Parameter (DAB)	Value	Parameter (Inverter)	Value
DAB V_{in}	650 V	Sampling T_s	25 us
V_{dc}	400 V	$V_{nominal}$	250 V
N_t	2	Grid volt.	312.5V
R; L; C	0.25Ω; 70uH; 1mF	Grid freq.	50Hz
PI (k_p; k_i)	7.53x10^3; 1.37x10^7;	L; C filter	50uH; 1.85mF

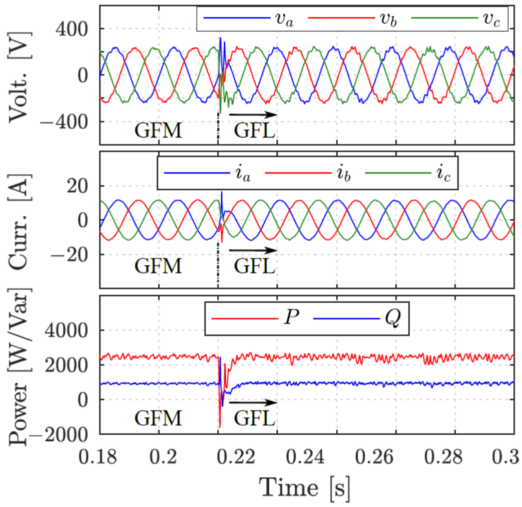

그림7 기존 GFM/GFL 제어에 대한 시뮬레이션 결과.

Fig.7 Simulation results for conventional GFM/GFL control.

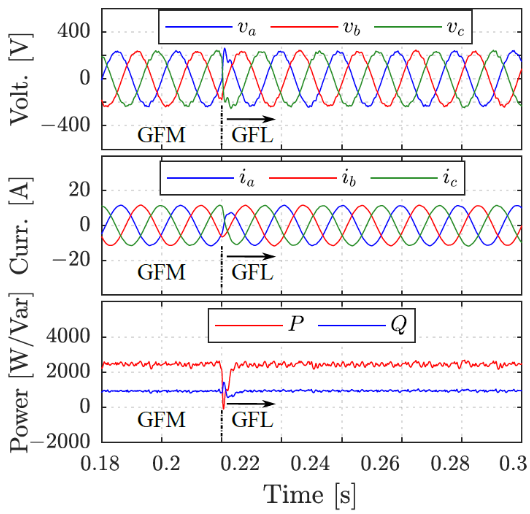

그림8 제안된 GFM/GFL 제어에 대한 시뮬레이션 결과.

Fig.8 Simulation results for proposed GFM/GFL control.

3. Conclusion

In this paper, the grid-forming SST for integrating solar PV with the distribution grid has been studied. The results show that the proposed control for the SST's dc/dc isolation stage and output inverter stage are capable of better disturbance rejection, faster dynamic response, and seamless transition between the SST's grid-forming and grid-following modes of operation. Future work will involve verification of the solution on a hardware prototype.

이 논문은 2024년도 정부(산업통상자원부)의 재원으로 한국에너지기술평가원의 지원을 받아 수행된 연구임 (20225500000100, 특고압 직류수전용 2MW급 모듈형 컨버터스테이션 기술개발).

This work was supported by Korea Institute of Energy Technology Evaluation and Planning (KETEP) grant funded by the Korea Government (MOTIE)(20225500000100, 2MW Modular-based MVDC-LVDC Converter Station).

참 고 문 헌

[1] Liu, Tao, et al. "High-efficiency control strategy for 10-kV/1-MW solid-state transformer in PV application." IEEE Transactions on Power Electronics, Vol. 35, No. 11, pp. 11770-11782, 2020.

[2] Z. Zou, J. Tang, M. Liserre, Z. Wang and M. Cheng, "Modeling and stability analysis of meshed smart transformer-fed grid," CSEE Journal of Power and Energy Systems, 2022 (Early access).