DOB-based Model Predictive Voltage Control for Electric Vehicle Charging Stations Integrated with Distribution Networks

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배전계통에 연계된 전기차 충전스테이션의 전압 안정화를 위한 모델예측제어

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Abstract

This paper proposes a method for improving the power quality of electric vehicle charging stations (EVCSs) with battery energy storage systems (BESSs) in distribution networks. The proposed approach is based on a disturbance observer (DOB) and model predictive voltage control (MPVC). As the number of EVCSs increases, challenges related to transformer overloading and power quality issues arise. Voltage fluctuations in local EVCSs are particularly problematic due to unpredictable EV charging loads and renewable energy production. The DOB estimates EV charging loads and PV generation power to ensure that the MPVC can effectively compensate for them and minimize voltage fluctuations. The proposed MPVC with DOB does not require a communication system and is obtained by solving a linear matrix inequality (LMI)-based optimization problem. Additionally, the study considers parameter uncertainties caused by inherent tolerances and aging degradation of circuit components. The proposed control scheme is evaluated using simulations and experiments with a 10 kVA EVCS simulator. Results demonstrate the effectiveness of the proposed approach.

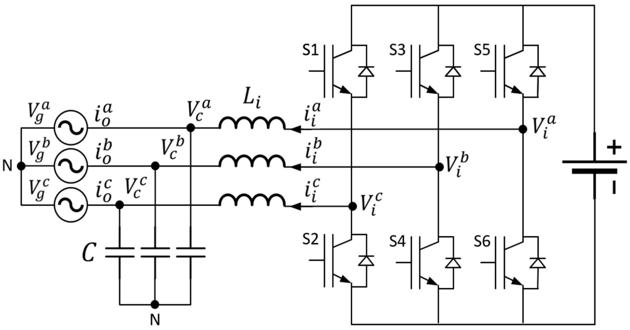
1. Introduction

The rise in electric vehicles (EVs) has led to an increase in demand for EV chargers, which can be categorized as single-phase slow EV chargers and three-phase fast EV chargers, both of which operate in connection with the existing distribution network. The integration of EV chargers, battery energy storage systems (BESS), and renewable resources has led to the development of electric vehicle charging stations (EVCSs), which function as microgrids in the low-voltage (LV) distribution network. However, this integration has introduced a new set of challenges, such as negative impact on distribution assets and power quality in the LV distribution network[1-2]. These issues include transformer overload, which can cause deterioration of the transformer's insulating paper and affect the voltage imbalance, harmonic distortion level, and voltage deviation in the distribution network. Moreover, fire accidents of EVs have occurred during charging or in the standby condition. Due to the relatively low reactance-to-resistance (X/R) ratio value of the LV network, the voltage of the LV distribution network fluctuates sensitively to the active and reactive power flows. This sensitivity is further exacerbated by the highly uncertain behavior of rapid EV charging loads and renewable energy production in EVCSs.

This paper focuses on addressing the challenges faced by the LV distribution network due to the increasing demand for EV chargers, particularly in the form of EV charging stations (EVCS) that integrate EV chargers, battery energy storage systems (BESS), and renewable resources. The paper highlights the negative impacts of the large volume of EVCS on distribution assets and power quality in the LV distribution network, such as transformer overload, voltage imbalance, harmonic distortion, and voltage deviation. The paper proposes a solution to these challenges by introducing a systematic design procedure to obtain the disturbance observer-based (DOB) and model predictive voltage control (MPVC) for the EVCS. The proposed method takes into account the parameter uncertainties of the line impedance and BESS inverter filters and ensures the performance of the DOB and MPVC against inherent tolerances and aging degradation. The DOB estimates the current generated by the PV system and EV charging load without additional external sensors and uses it to set the cost function of the MPVC to minimize the voltage fluctuation even in short-term voltage instability of the EVCS. The proposed method does not require establishing a communication system with peripheral power equipment and maintains a stable voltage without directly controlling the EV charging load, thereby not harming the stability of the onboard EV battery.

2. System description and Controller design

Fig. 1 shows the standard configuration of a bidirectional three-phase inverter that uses an LC filter in BESS applications.



[Fig. 1] Three-phase grid-connected inverter with LC filter

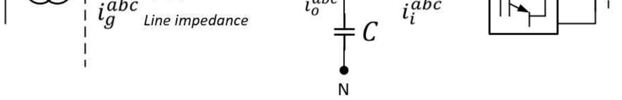
The system dynamics of the LC filter can be represented by applying Kirchhoff's law as follows:

$$V_i^{abc} = L_i \frac{di_i^{abc}}{dt} + V_c^{abc} \tag{1}$$

$$i_i^{abc} = C\frac{dV_c^{abc}}{dt} + i_o^{abc} \tag{2}$$

$$V_c^{abc} = L_g \frac{di_g^{abc}}{dt} + R_g i_g^{abc} + V_g^{abc} \tag{3}$$

The distribution network, where EVCS is commonly integrated with distributed energy resources, has a low reactance-to-resistance ratio (X/R) compared to the transmission network. Hence, the dynamic model of EVCS must consider the line impedance, which can be represented using Fig. 2.



[Fig. 2] EVCS with line impedance in the distribution network.

$$\frac{di_i^{dq}}{dt} = wMi_i^{dq} - \frac{1}{L_i}V_c^{dq} + \frac{1}{L_i}V_i^{dq} \tag{4}$$

$$\frac{dV_c^{dq}}{dt} = \frac{1}{C}i_i^{dq} + wMV_c^{dq} - \frac{1}{C}i_o^{dq} \tag{5}$$

$$\frac{di_g^{dq}}{dt} = \frac{1}{L_g}V_c^{dq} + \left(wM - \frac{R_g}{L_g}\right)i_g^{dq} - \frac{1}{L_g}V_g^{dq} \tag{6}$$

The parameters may vary owing to inherent tolerances and aging degradation; therefore, parameter uncertainty must be included in the equations.

$$\begin{bmatrix} \mathbf{Q_o} & \mathbf{Z^T} & (\mathbf{A}_i\mathbf{Q} + \mathbf{B}_i\mathbf{Z})^{\mathbf{T}} \\ \mathbf{Z} & \mathbf{R^{-1}} & 0 \\ (\mathbf{A}_i\mathbf{Q} + \mathbf{B}_i\mathbf{Z}) & 0 & \mathbf{Q} \end{bmatrix} > 0 \quad (i = 1,2,\cdots,N) \tag{7}$$

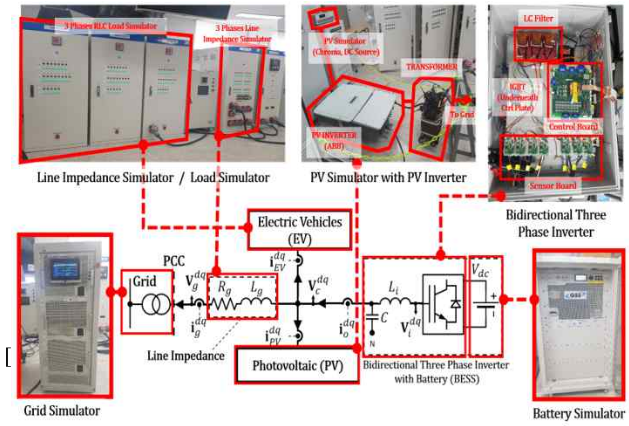
3. Experimental result

In this section, we present the experiment results to demonstrate the effectiveness of the proposed MPVC method. The nominal values of each component, such as the inverter with the LC filter and the line impedance in the EVCS, are listed in Table I.

[Table 1] System Parameters

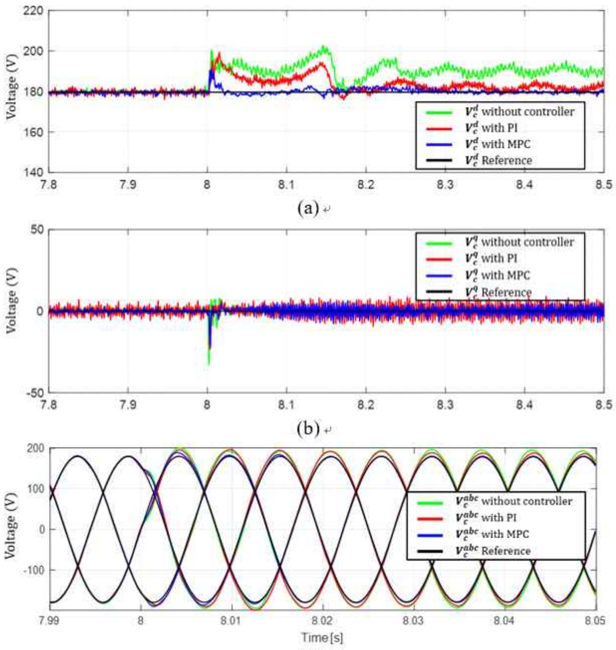
Description	Value
Grid voltage (Line - Line)	220 V
Grid frequency	60 Hz
DC-link voltage (Nominal)	600 V
Inverter side inductance	2 mH
Filter capacitance	10 uF
Line impedance R	1.0 Ohm
Line impedance L	1.326 mH
Switching time	100 µs

To validate the proposed MPVC scheme, an experimental setup was configured as depicted in Fig 3. The setup includes a battery simulator, a grid simulator, a PV simulator, a PV inverter, a line impedance simulator, and a load simulator. The MPVC control scheme was implemented using TMS320F28377D with sensor interface boards and was mounted on a grid-connected inverter. The grid simulator was used to mimic the experimental conditions and perform grid condition monitoring.



[Fig. 3] Experimental environment of EVCS

The experimental results of the proposed MPVC and the cases with the comparative methods are presented in Fig. 4. The PV system consists of a PV simulator, an inverter that generates PV power with 2.5 kW at 8 s. The output voltage is shown d-q frame in Fig. 4(a), 4(b), and 4(c), and presents the three-phase output voltage of the stationary frame. It was confirmed that the grid voltage reached immediately the reference value as soon as PV power generation started; this is clearly shown by the fact that the d-q voltage fluctuation magnitude is much smaller than that of the PI controller. In this case, the disturbances and indicate the amount of current generated by the PV and estimated by the DOB are shown in Fig. 5.

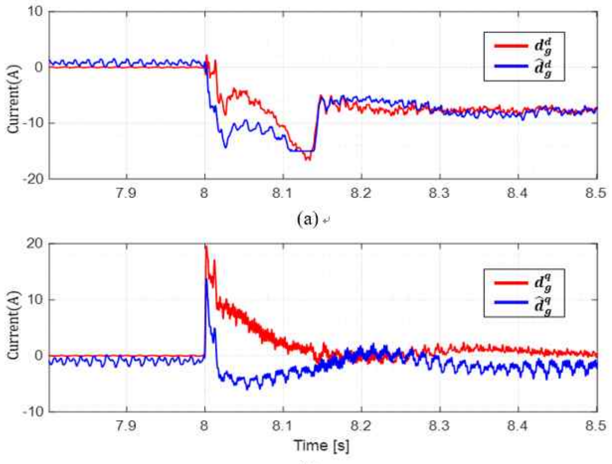


(a)

(b)

(c)

[Fig. 4] Experimental results of the grid voltage in EVCS when PV power generation is applied to EVCS at 8.0 s. (a) Without controller, with PI controller, with MPVC controller, and reference voltage in the *d*-axis. (b) Without controller, PI controller, with MPVC controller, and reference voltage in the *q*-axis. (c) Without controller, with PI controller, with MPVC controller, and reference voltage in 3-phase voltage.



(a)

(b)

[Fig. 5] Experimental results of the disturbance in EVCS when PV power generation is applied to EVCS at 8.0 s. (a) Measured current and estimated current in *d*-axis. (b) Measured current and estimated current in *q*-axis.

5 Conclusion

The paper proposes a BESS-based direct method for grid voltage instability compensation without EMS, which considers parameter uncertainties and stability analysis in its design. Additionally, a DOB-based MPVC control scheme is proposed for improving the power quality of EVCS without the need for a communication system. The effectiveness of the proposed methods is validated through simulations and experiments, demonstrating good current estimation and voltage control performance against disturbances.

감사의 글
본 연구는 2022년도 산업통상자원부의 재원으로 한국에너지기술평가원(KETEP)의 지원을 받아 수행한 연구 과제입니다.(No. 20223030020110)
본 연구는 2021년도 중소벤처기업부의 재원으로 중소기업기술정보진흥원(TIPA)의 지원을 받아 수행한 연구 과제입니다.(No. S3177509)

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