Analysis and Control of a Transformerless Series Injector Based on Paralleled H-Bridge Converters for Measuring Impedance of Three-Phase AC Power Systems

Zeng Liu*, Igor Cvetkovic†, Zhiyu Shen‡, Dushan Boroyevich†, Rolando Burgos†, and Jinjun Liu*
*State Key Lab of Electrical Insulation and Power Equipment, Xi'an Jiaotong University, Xi'an, Shaanxi, China
† Center for Power Electronics Systems, Virginia Polytechnic Institute and State University, Blacksburg, VA, United States
‡General Electric Global Research Center, Niskayuna, NY, United States
Email: zeng.liu@ieee.org

***Abstract*—Small-signal stability of AC power systems is able to be predicted by measuring their terminal impedances, and the transformerless series injector is attractive for measuring load subsystem impedance in wide frequency range. The series injector paralleling H-bridge converters is studied in this paper, where the DC voltage unbalance mechanism is analyzed by modeling the active power flow of the converters, and it is revealed that a positive feedback exists under the situation of high system current. Furthermore, an enhanced control scheme is proposed to make the series injector operate in full system current range. Finally, the theoretical analysis is verified by hardware test results.**

Keywords—small-signal stability; impedance measurement; series injector; H-bridge converters; DC voltage balance

I. Introduction

Three-phase AC power systems are prone to small-signal instability due to the dynamic behaviors of individual power equipment, such as power electronics converter [1-3]. This phenomenon can be effectively analyzed by dividing the whole system into a source subsystem and a load subsystem at the bus, and then applying Generalized Nyquist Criterion (GNC) to their small-signal terminal impedances defined under synchronous reference frame (SRF) [4, 5]. Thus, in practical, extraction of terminal impedance is becoming significant for assessing system stability.

The basic principle of extracting small-signal impedances of three-phase AC systems has been well established [6-8]. Small perturbation signal at various selected frequencies under SRF are injected into the system. Corresponding responses of current and voltage at the terminal of subsystems are measured and then processed to compute the impedance of subsystems over the frequency range of interest. The perturbation injector is the core component for the impedance measurement, because it is electrically connected to the system under measurement. The shunt injector is initially proposed for measuring impedance of AC power systems, which is parallel to the system bus, and injects perturbation current into the system [9-11]. However, the shunt injector is just good for measuring the impedance of source subsystem, since most of perturbation current will flow into source subsystem whose impedance is usually much lower than the load subsystem. In order to accurately measure the impedance of load subsystem, the series injector has been proposed [10, 12, 13], which is inserted in series between the two subsystems and injects perturbation voltage into the system. In [10], a three-phase bridge converter is used for generating perturbation voltage. Its terminals are coupled to the system through a transformer to boost the current capability of the injector. However, the lowest measurement frequency is limited due to the saturation of the interface transformer. Then a transformerless series injector is proposed in [12, 13], where multiple H-bridge converters are paralleled at their AC sides for current capability boosting and then inserted between the two subsystems directly. Thus, this injector is very attractive for measuring impedance of load subsystem in a wide frequency range.

In the series injector paralleling H-bridge converters, the system current should be shared among H-bridge converters, while their DC voltages must be balanced and equal to the reference since their DC links are isolated and floating. To achieve these objects, a control scheme has been proposed in [12], where DC voltage balancing loops and inductor current loops are employed, and the DC voltage balancing control is realized by trimming the reference of inner inductor current loop. As shown in the test results under low system current, the system current is shared among H-bridge converters and their DC voltages is balanced. However, it is interesting to find that the DC voltages of H-bridge converters are not balanced any more when the magnitude of system current reaches and exceeds a certain point, which is much less than designed current rating. Therefore, the series injector controlled by existing scheme is just able to operate under low system current, and the measurement capability is seriously limited.

To tackle the aforementioned problem, this paper presents a deep analysis on the mechanism behind DC voltages being unbalanced. It is revealed that a positive feedback appears in the DC voltages balancing loop when system current is larger than a certain point. Furthermore, an enhanced control scheme is proposed for the transformerless series injector, where reactive circulating currents among the H-bridge converters are introduced to balance DC voltages, and the series injector is able

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to operate in full system current range. Finally, the theoretical analysis is verified by experimental results.

II. System Configuration

Fig. 1 shows the typical configuration of impedance measurement for a three-phase AC power system divided into the source subsystem and the load subsystem. The series injector is inserted into phase A for injecting perturbation voltage v_p to the whole system, while terminal voltage and current of source and load will be measured and processed for computing their impedance $\mathbf{Z}_{Sdq}$ and $\mathbf{Z}_{Ldq}$.

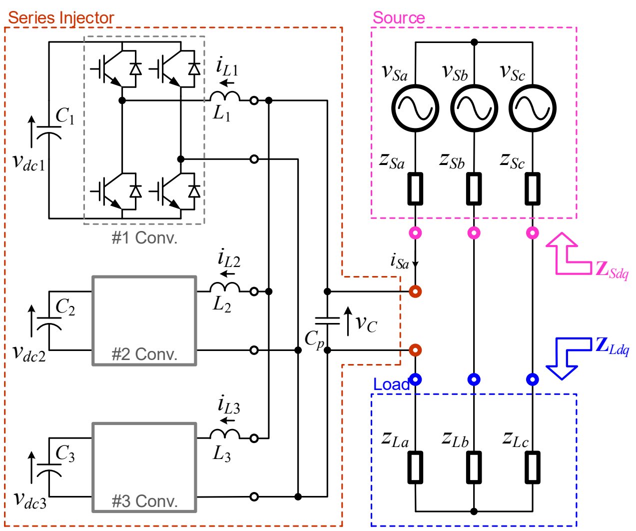


Fig.1 Impedance measurement setup for three-phase AC power system using a transformerless series injector based on three H-bridge converters.

In the series injector, three H-bridge converters, composed by four IGBTs with anti-parallel diodes, are just covered for simplification. Their AC side are paralleled together through the inductor L_k (k = 1, 2, 3), while there is just a floating capacitor C_k on their DC sides for maintaining the DC voltage of H-bridges. Besides, an AC capacitor C_p is adopted for buffering the system current i_{Sa}. In the normal operation of series injector, perturbation voltage at given frequency is generated on the AC capacitor C_p, and system current i_{Sa} is equally shared among H-bridge converters while their DC voltages v_{dck} follow the voltage reference.

III. Analysis on DC Voltages Unbalance Mechanism in Existing Control Scheme

A. Description of Existing Control Scheme

For the series injector, there are four control targets, which are 1) average DC voltage regulation, 2) system current sharing among H-bridge converter, 3) DC voltages balancing, and 4) perturbation voltage generation. The block diagram of existing control scheme is shown in Fig. 2, which is mainly composed by triple cascaded loops, i.e. external average DC voltage loop, medium AC capacitor voltage loop, and inner inductor current loops.

The first control target is realized by external average DC voltage loop. The average DC voltage depends on the active power absorbed by the injector, thus the output of average DC voltage regulator G_{VDC} is multiplied by the phase information of system current $\cos\theta$, obtained by a phase-locked loop (PLL), to generate instantaneous active reference v_{Cf}^* for the middle AC voltage loop. The second control target is achieved by inner inductor current loop of each H-bridge converter, and the output of inductor current regulator G_{IL} sets the duty cycles d_k for semiconductor switches of H-bridges. The third target is met by regulating the active power of each converter through trimming the system current distribution among converters, thus the inductor current reference of each converter is adjusted by adding a small variable Δi_{Lk}^*, which is generated by the DC voltage balance compensator G_{ILt}. The fourth target is realized by adding the perturbation reference v_p^* as a part of instantaneous reference of AC capacitor voltage v_C^*.

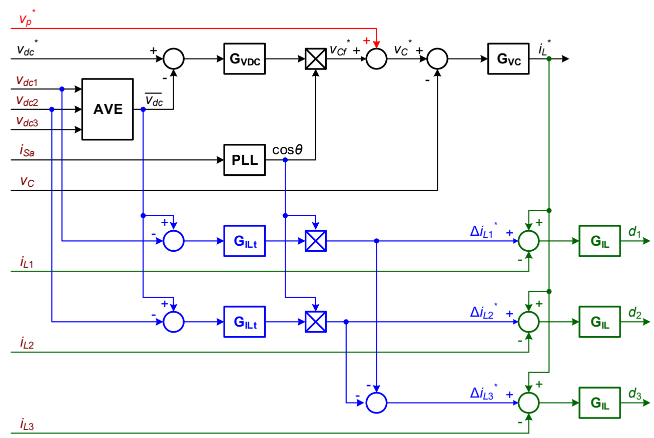


Fig. 2 Block diagram of existing control scheme for the transformerless series injector.

B. Modeling of Active Power Flow

Since the DC capacitor voltage is related to active power, the active power flow in H-bridge converters will be modeled. It is assumed that the steady state error of the inner inductor current loop, and the middle AC capacitor voltage loop at fundamental frequency is zero, since their bandwidths are much higher than the fundamental frequency.

The components of perturbation frequency in the system current and AC capacitor voltage are neglected in the active power modeling, which are expressed by (1) and (2).

$$i_{Sa} = I_{Sam}\cos\theta \tag{1}$$

$$v_C = V_{Cpm}\cos\theta \tag{2}$$

It is assumed that the current of AC capacitor is negligible since its capacitance C_p is very small, and the inductor current of each H-bridge converter is expressed by (3). Moreover, the relationship among them and the system current is shown in (4).

$$i_{Lk} = I_{Lkpm}\cos\theta \tag{3}$$

$$\sum_{k=1}^{3} I_{Lkpm} = I_{Sam} \tag{4}$$

Using the inductor current and the capacitor voltage above, the average active power absorbed by each H-bridge converter can be derived as (5), which equals to the sum of the power loss of the inductor P_{Lk}, the power loss of semiconductor devices P_{Tk} and the power flowing into DC side P_{dck}, and their relationship is represented by (6).

$$P_{Ik} = \int v_C i_{Lk} dt = \frac{1}{2} V_{Cpm} I_{Lkpm} \tag{5}$$

$$P_{Ik} = P_{Lk} + P_{Tk} + P_{dck} \tag{6}$$

The power loss of the inductor P_{Lk} composed by copper loss and core loss, which is approximately proportional to the square of RMS value of its current [14], is expressed by (7).

$$P_{Lk} = \frac{1}{2} R_{Lk} I_{Lkpm}^2 \tag{7}$$

Moreover, since the IGBTs and diodes are used as semiconductor switches, and their power losses, composed by switching loss and conduction loss, are approximately proportional to the magnitude of AC side current [15], which is presented by (8).

$$P_{Tk} = M_{Tk} I_{Lkpm} \tag{8}$$

Combining (5)-(8) together, the operation point of the AC capacitor voltage magnitude can be derived as (9). It is found that the AC capacitor voltage magnitude will decrease and then increase with the inductor current magnitude.

$$V_{Cpm} = R_{Lk} I_{Lkpm} + 2M_{Tk} + \frac{2P_{dck}}{I_{Lkpm}} \tag{9}$$

C. Analysis on DC Voltage Balance Control

In existing control scheme, the DC voltage balancing is regulated by trimming the inductor current magnitude, and thus it is useful to derive the differential relationship between the power flowing into DC side P_{dck} and the inductor current magnitude I_{Lkpm} for each H-bridge converter. Firstly, the steady state relationship between them can be obtained by combining (5)-(8), and is given in (10).

$$P_{dck} = \frac{1}{2} V_{Cpm} I_{Lkpm} - \frac{1}{2} R_{Lk} I_{Lkpm}^2 - M_{Tk} I_{Lkpm} \tag{10}$$

Then their differential relationship can be derived from (10), and is shown in (11) by substituting (9).

$$\frac{\Delta P_{dck}}{\Delta I_{Lkpm}} = \frac{P_{dck}}{I_{Lkpm}} - \frac{1}{2} R_{Lk} I_{Lkpm} \tag{11}$$

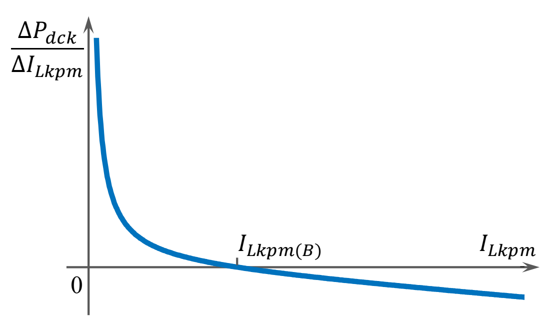


Fig. 3 Variation of the differential ratio of the power flowing against the inductor current magnitude in the H-Bridge converter.

As shown in Fig.3, the differential ratio of the power flowing into DC side against the inductor current magnitude will be positive when the operation point inductor current magnitude is low, and be negative when it is high, and the boundary is given by (12).

$$I_{Lkpm(B)} = \sqrt{\frac{2P_{dck}}{R_{Lk}}} \tag{12}$$

It means that when the inductor current magnitude is lower than the boundary $I_{Lkpm(B)}$, power flowing into DC side P_{dck} will increase with the increase of inductor current magnitude I_{Lkpm}, and the DC voltage balancing regulation works well. When the inductor current magnitude exceeds the boundary, power flowing into DC side P_{dck} will decrease with the increase of inductor current magnitude I_{Lkpm}, and the positive feedback appears in the DC voltage balancing loop.

In the steady state, the power flowing into DC side P_{dck} equals to the power loss of the DC capacitor C_k. Generally, the power loss of DC capacitor is much less than power loss of inductor in H-bridge converters, and thus the boundary shown in (12) is much less than the inductor current rating.

IV. Enhanced Control Scheme

In order to make the injector operates up to the full inductor current range, this paper proposes an enhanced control scheme, whose block diagram is shown in Fig. 4.

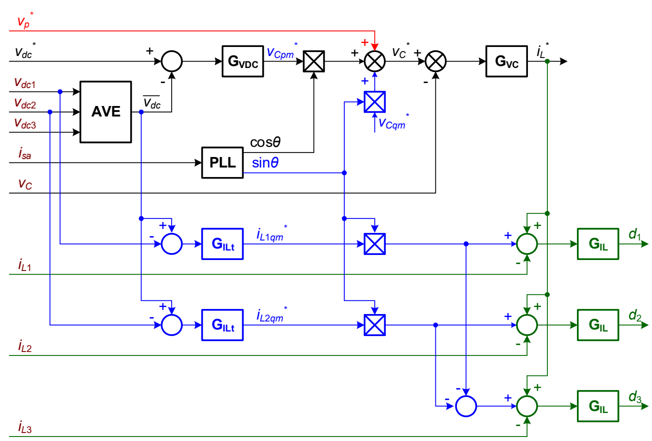


Fig. 4 Block diagram of proposed control scheme for the transformerless series injector.

First, a reactive reference $V_{Cqm}{}^*$ is added in the medium AC capacitor voltage loop, and the AC capacitor voltage can be expressed by (13).

$$v_C = V_{Cpm} \cos\theta + V_{Cqm} \sin\theta \tag{13}$$

The overall active power absorbed by the series injector is not changed by this reactive reference, and the original overall DC voltage loop is not influenced.

Second, the DC voltage balancing regulator G_{ILt} sets a reactive current reference for the inductor current in each converter, and the active power absorbed by each converter can be controlled by regulating its reactive current reference

$I_{Lkqm}{}^{*}$ according to (14), where I_{LPm} denotes the active component of the inductor current determined by $i_L{}^{*}$.

$$P_{Ik} = \frac{1}{2} V_{Cpm} I_{Lpm} + \frac{1}{2} V_{Cqm} I_{Lkqm} \tag{14}$$

Moreover, the differential ratio of power flowing into DC side against reactive current magnitude can be derived as (15), which is always positive with proper V_{Cqm}. Therefore, the series injector with proposed control scheme is able to operate in full system current range.

$$\frac{\Delta P_{dck}}{\Delta I_{Lkqm}} \approx V_{Cqm} - 2R_{Lk} I_{Lkqm} - \frac{M_{Tk}}{I_{Lpm}} I_{Lkqm} \tag{15}$$

V. Experimental Results

The hardware setup of series injector paralleling three H-bridge converters has been built in the lab, which is shown in Fig. 5. The parameters of the H-bridge converters are listed in TABLE I, which are targeted at measuring impedance of three-phase AC system with current rating of around 24A from 0.1Hz to 1kHz.

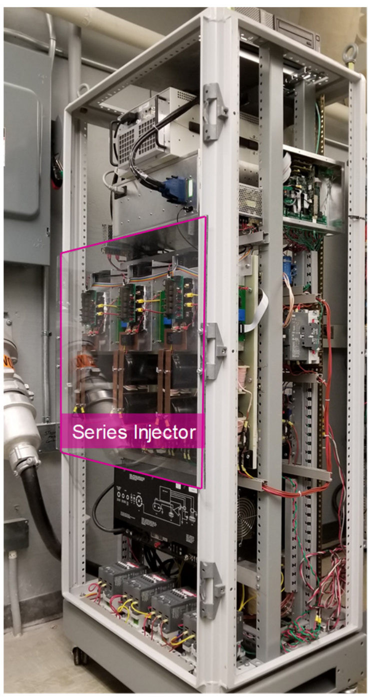
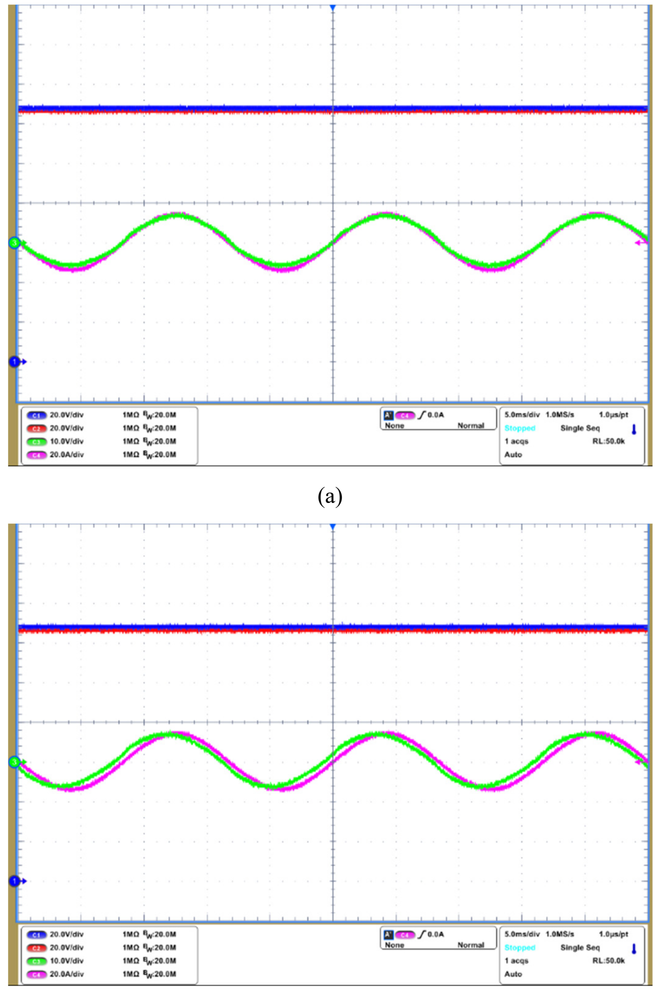


Fig. 5 Photograph of impedance measurement setup composed by a series injector paralleling three H-bridge converters.

TABLE I. Parameters of H-bridge Converter in the Hardware Setup of Series Injector

Parameters	Value
Filter inductor L_k	0.33 mH
AC capacitor C_p	66 µF
DC capacitor C_k	16.4 mF
Switching frequency f_s	10 kHz
DC voltage reference $v_{dc}{}^{*}$	130 V

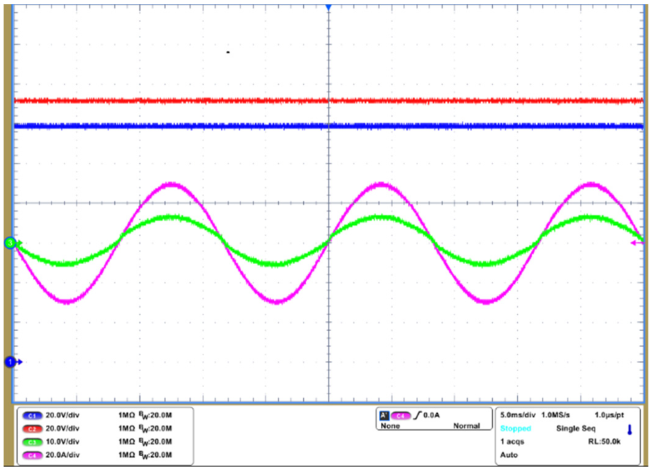
Experimental tests have been done to verify the theoretical analysis. The test results under low system current with existing control scheme and proposed one are shown in Fig. 6, while the test results under high system current are shown in Fig. 7. It can be found that with existing control scheme the DC voltages are balanced under low system current, and are unbalanced under high system current. Moreover, it is obvious that with the proposed control scheme, the DC voltages are always balanced. Therefore, the theoretical statements are verified.



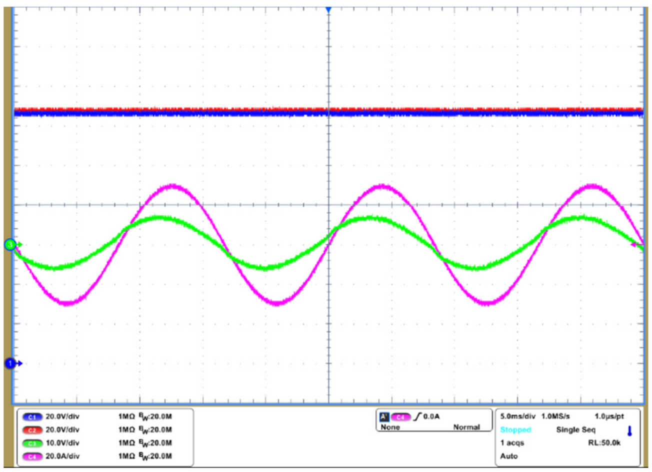
(a)

(b)

Fig. 6 Experimental waveforms of the series injector when I_{Sa} = 12A, $v_p{}^{*}$=0V under (a) existing control scheme and (b) proposed control scheme where $v_{Cqm}{}^{*}$ = 2V: CH1, v_{dc1}, 20V/div; CH2, v_{dc2}, 20V/div; CH3, v_C, 10V/div; CH4, i_{Sa}, 20A/div.



(a)



(b)

Fig. 7 Experimental waveforms of the series injector when I_{Sa} = 24A, v_p^*=0V under (a) existing control scheme and (b) proposed control scheme where v_{Cqm}^* = 2V: CH1, v_{dc1}, 20V/div; CH2, v_{dc2}, 20V/div; CH3, v_C, 10V/div; CH4, i_{Sa}, 20A/div.

VI. Conclusion

A transformerless series injector paralleling H-bridge converters for impedance measurement is studies in this paper. The mechanism of DC voltage unbalance in existing control scheme is analyzed. It reveals that a positive feedback appears in the DC voltage-balancing loop when system current exceeds the derived boundary. Furthermore, an enhanced control scheme is proposed to make the series injector operate in full system current range by introducing both reactive voltage on AC capacitor and reactive circulating current among H-bridge converters for redistributing active power among them. The theoretical analysis is validated by experiment. The proposed control scheme enlarges the system current capability of the impedance measurement with the series injector.

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