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***Abstract*—The asymmetry of the inherent distributed capacitances causes the rise of neutral-to-ground voltage in ungrounded system or high resistance grounded system. Overvoltage may occur in resonant grounded system if Petersen coil is resonant with the distributed capacitances. Thus, the restraint of neutral-to-ground voltage is critical for the safety of distribution networks. An active grounding system based on single-phase inverter is proposed to achieve this objective. Relationship between output current of the system and neutral-to-ground voltage is derived to explain the principle of neutral-to-ground voltage compensation. Then, a current control method consisting of proportional resonant (PR) and proportional integral (PI) with capacitive current feedback is then proposed to guarantee sufficient output current accuracy and stability margin subjecting to large range of load change. The performance of the control method is presented in detail. Experimental results prove the effectiveness and novelty of the proposed grounding system and control method.**

Keywords—grounding method, neutral-to-ground voltage, inverter, load effect, current detection, current control method

I. INTRODUCTION

Either in theory or practice, the major objective of grounding system in distribution networks is to restrain the line-to-ground fault current to extinguish the arcs caused by the grounding fault. However, the other purpose of grounding system is commonly disregarded, that is, to control the neutral-to-ground voltage within certain limit [1]. This is critical for the safety of the power system especially when the inherent asymmetrical voltage is high.

Asymmetrical voltage directly determines the neutral-to-ground voltage in ungrounded system or high resistance grounded (HRG) system [2]. It is caused by the asymmetry of the distributed coefficients. Several reasons may cause the asymmetry, including inappropriate transposition in overhead lines, medium voltage single phase load [3], etc. Moreover, the neutral-to-ground voltage is closely related to the grounding method. Obviously, it is limited to a small value in an effectively grounded system. Whereas, in resonant grounded (RG) system, it may even exceed the line-to-neutral voltage as resonance between the Peterson coils and inherent distributed capacitances happens [4]. For the purpose of maintaining power supply reliability and extinguishing fault arcs, most medium voltage distribution networks adopt HRG or RG method, which makes the problem of high neutral-to-ground voltage unavoidable.

Several measures are taken to limit the neutral-to-ground voltage in ineffectively grounded systems [3]. Transposition enhancement is a commonly used method for overhead lines to decrease the asymmetrical voltage. However, this method needs huge amount of work and is complicated to implement. Three phase coupling capacitances are used to balance the distributed inherent capacitances and thus decrease the asymmetrical voltage. Nevertheless, it is not flexible enough to adapt the change of operation modes and is even likely to undermine the asymmetrical voltage in some conditions. Improvement of detuning ratio and damping ratio in RG systems can decrease the neutral-to-ground voltage caused by the aforementioned resonance [4]. However, this method is not able to eliminate the neutral-to-ground voltage caused by the asymmetry.

For the purpose of eliminating the neutral-to-ground voltage, an active grounding system is needed with the characteristics that it is able to inject certain currents to the neutral point and make it seem like short-circuited to the ground. Obviously, this system cannot be realized by passive components as resistor, reactor or capacitor. Thus, a single-phase inverter based grounding system is adopted to fulfill these features.

The current control method are essential to the control system of an inverter. It stands for the inverter based grounding system as well. The equivalent load of the inverter is nearly capacitive and it is likely to be resonant with the LC filter of inverter at around fundamental frequency, which may bring about steady state error and undermine stability margin of the control system. These features make the structure and parameter design of the active grounding system complicated. Several literatures have addressed the load effect and resonance phenomena, and many effective measures have been proposed [5]-[8]. Literature [5] proposed a mixed controller of proportional integral differential (PID) and

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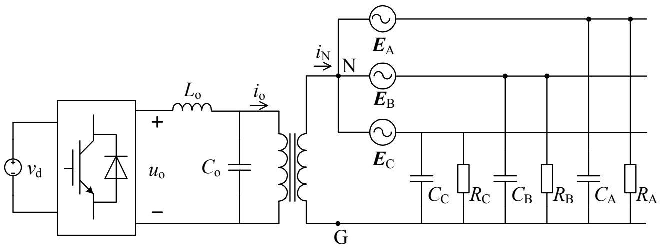

Fig. 1 Topology of distribution network and active grounding system

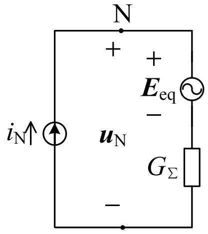

Fig. 2 Simplified circuit of the distribution network

Resonant plus load current feedback to reduce the steady state error and improve the dynamic response while dealing with different load types. But the parameters of the controller is not discussed in detail. Literature [6] discussed the inherent instability of LCL filter in active power filter and introduce the active damping method of capacitive current feedback to improve the stability margin. Degradation method can simplify the design of control system for LCL filter [8]. However, as the load type of the grounding system are different from LCL filter, these method cannot be adopted without modification.

In this paper, the relationship between output current of the grounding system and the neutral-to-ground voltage is firstly derived. Then, the load effect and resonance phenomena are addressed in detail, followed by a current control topology design strategy. Experimental results for validation of the proposed control topology and design method are subsequently provided.

II. PRINCIPLE OF ACTIVE GROUNDING SYSTEM

The topology of distribution network and active grounding system is shown in Fig. 1. E_A, E_B, E_C are the three phase voltages. The phase-to-ground capacitance and leakage resistance of phase X (X=A, B or C) are C_X and R_X, respectively. The grounding system is composed of a single phase full-bridge inverter, a LC-type output filter, and a coupling transformer. The output current of the system is controlled by the PWM pulses of IGBT to execute compensation current detection and neutral-to-ground voltage compensation. The transformer is used to regulate the output voltage of the inverter and protect the system in case of neutral overvoltage while single phase ground fault happens.

Assuming that the output current of the inverter is totally under control, then the grounding system can be treated as an ideal current source. According to circuit theories, the partition of distribution network can be simplified by a voltage source in series with an impedance. Therefore, the circuit of the whole system can be simplified to Fig. 2.

In Fig. 2, $\boldsymbol{E}_{eq}$ and G_Σ denote the voltage and impedance of the equivalent voltage source and the impedance of the distribution network, respectively. They can be obtained by following expressions. Y_X is the phase-to-ground admittance of phase X, that is $Y_X=j\omega_0C_X+1/R_X$.

$$\boldsymbol{E}_{eq} = -G_\Sigma(\boldsymbol{E}_A Y_A + \boldsymbol{E}_B Y_B + \boldsymbol{E}_C Y_C) \quad (1)$$

$$G_\Sigma = \frac{1}{Y_\Sigma} = \frac{1}{Y_A + Y_B + Y_C} \quad (2)$$

Therefore, the relationship between the output current of the grounding system $\boldsymbol{i}_N$ and the neutral-to-ground voltage $\boldsymbol{u}_N$ is

$$\boldsymbol{u}_N = \boldsymbol{i}_N G_\Sigma + \boldsymbol{E}_{eq} = G_\Sigma(\boldsymbol{i}_N - \boldsymbol{E}_A Y_A - \boldsymbol{E}_B Y_B - \boldsymbol{E}_C Y_C) \quad (3)$$

Obviously, if $\boldsymbol{i}_N$ can be controlled to certain value that satisfy (4), then the neutral-to-ground voltage comes to zero, which means the asymmetry of distribution network is fully compensated.

$$\boldsymbol{i}_0 = \boldsymbol{E}_A Y_A + \boldsymbol{E}_B Y_B + \boldsymbol{E}_C Y_C \quad (4)$$

It can be further concluded that the compensation current also meets expression (4) while a Petersen coil or resistor is parallel connected to the grounding system. That indicates the grounding system is suitable for distribution network both HRG and RG grounding method.

III. CURRENT CONTROL STRATEGY

A. Open-loop transfer function

As the magnitude and frequency of three phase voltages rarely change, we disregard these voltages during the control system analysis. The main circuit is thus simplified to Fig. 3.While conducting the current control, a typical method is to use output current feedback. Fig. 4 shows the feedback control diagram of the system. From this diagram, the relationship between modulation signal v_m and inverter output current i_o is presented by G_1

$$G_1(s) = \frac{i_o(s)}{v_m(s)} = \frac{K_{pwm}(sR_sC_s+1)}{s^2R_sL_o(C_o+C_s)+sL_o+R_s} \quad (5)$$

As L_o, the inductance of LC filter, is usually set to be small, resonance occurs when the frequency comes to ω_r

$$\omega_r = \sqrt{\frac{1}{L_o(C_o+C_s)}} \quad (6)$$

Fig. 5 shows the bode diagram of G_1 with typical parameters listed in TABLE I. The parameters of distribution network are set to be right the same as that of a real one with certain charging current of 50A. In Fig. 5, resonance in ω_r can be obviously observed. This resonance brings about -180° phase shift to G_1. The resonant frequency is related to C_s, which varies with the distribution network. If the frequency locates in the low frequency band, the steady state error might increase. Fig. 5 also shows bode diagrams as C_s varies from nominal value, 60%, and 30% of that value. Magnitude in fundamental frequency decreases from 67.7dB to 47.1dB as C_s decreases, which means a significant increase in steady state error at fundamental frequency. Moreover, if the resonant frequency locates in the medium band, the phase margin of the control system might decrease. In order to guarantee a small

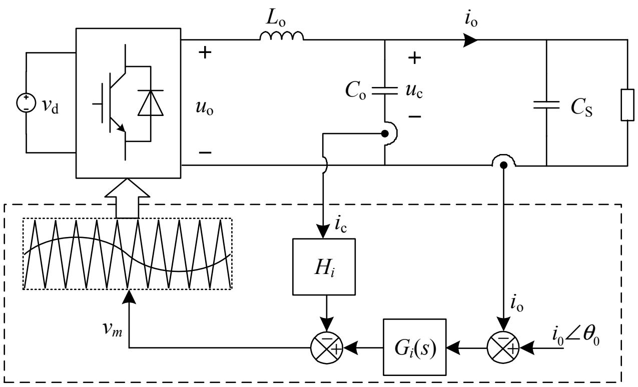

Fig. 3 Simplified main circuit

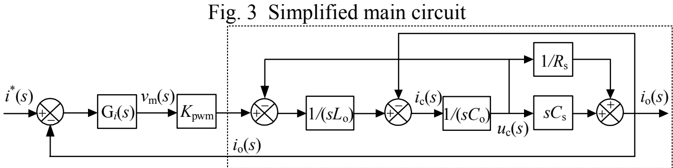

Fig. 4 Control diagram with only output current feedback

steady state error in fundamental frequency, the proportional resonance controller is usually adopted [9]. The bode diagram of PR controller is also drawn in Fig. 6. It can be seen from Fig. 6 that the controller not only brings about pretty much magnitude in fundamental frequency, but also a -180° phase shift around the same frequency. The crossover frequency ω_c is always set to be in the medium band, which is probably larger than ω_r and the fundamental frequency, as a result, the phase margin of the whole control system $G_C(s)= G_{PR}(s)G_1(s)$ approaches zero, which makes the system easily unstable.

From the analysis above, the resonance should be carefully damped to meet control system requirement. Typically, a parallel resistor in the C_o branch is adopted which refers to the passive method [10]. However, this method suffers from considerable loss, making it not practical enough.

B. Capacitive current feedback

This paper presents an active damping method that flexibly damps the resonance without any loss. Fig. 8 shows the control diagram of the proposed method. In this method, the current of C_o is feedback to the control loop with a ratio of H_i. The open-loop transfer function of the feedback control system is presented by G_2 in (7). The capacitive current feedback introduces a ratio of $K_{pwm}H_iR_sC_o$ to the s term of the denominator. As a result, the magnitude of G_2 decrease significantly at the original resonant frequency ω_r, which effectively damps the control system. Fig. 7 shows bode diagram comparison of the original system and damped system. It is clear that capacitive current feedback damps the magnitude at the resonant frequency and enhances the phase margin of the system. As the feedback ratio H_i increases, the damping degree rises, which means less magnitude in resonant frequency and larger phase margin in medium band. Meanwhile, the capacitive current feedback also brings about a decreased magnitude at fundamental frequency, which undermines the steady state performance of the control system. Therefore, the current controller must have significant magnitude at fundamental frequency to maintain a relatively

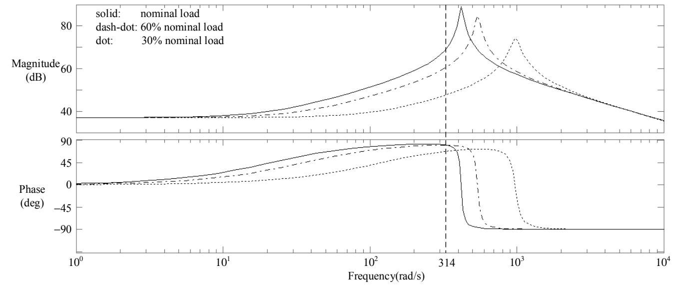

Fig. 5 Bode diagrams of $G_1(s)$ when C_s varies

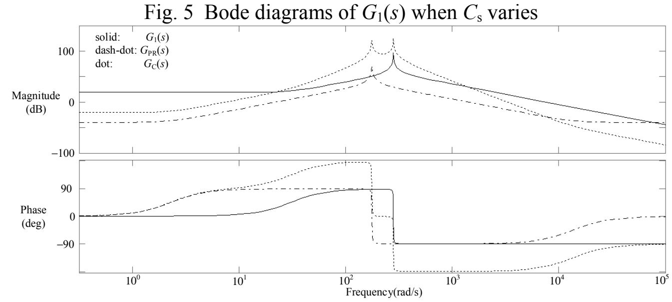

Fig. 6 Bode diagrams of $G_1(s)$, $G_{PR}(s)$ and $G_C(s)$

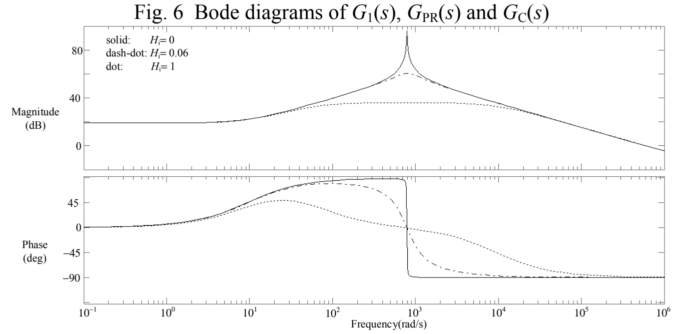

Fig. 7 Bode diagrams comparison of $G_1(s)$ and $G_2(s)$ with various H_i

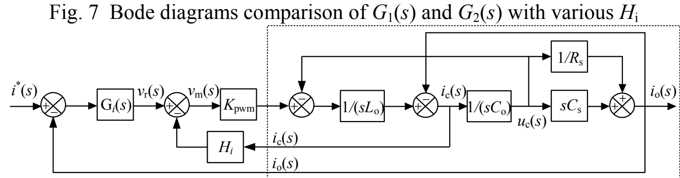

Fig. 8 Control diagram with proposed capacitive current feedback

small steady state error.

$$G_2(s)=\frac{i_o(s)}{v_r(s)}=\frac{K_{pwm}(sR_sC_s+1)}{s^2R_sL_o(C_o+C_s)+s(L_o+K_{pwm}H_iR_sC_o)+R_s} \quad (7)$$

C. Current Controller

PR controller has the advantage of great magnitude at specified frequencies, thus it is normally used for sinusoidal signal regulation. In case that the frequency of distribution network varies, the controller is in the damped form, that is

$$G_{PR}(s)=k_{p\_PR}+\frac{2k_r\omega_i s}{s^2+2\omega_i s+\omega_0^2} \quad (8)$$

In (8), ω_0 is the fundamental angular frequency. k_{p_PR} and k_r denote the proportional and resonant ratio, respectively. The sum of them determines gain of the controller at fundamental frequency. ω_i is the resonant cutoff frequency which mainly concerns about the magnitude and phase of the controller around the resonant frequency. It is set to a typical value of π when dealing with 1% variation of fundamental frequency [11].

The magnitudes of PR controller in both low and high frequency band are determined only by the proportional ratio k_{p_PR}. To avoid the interference of high frequency signal, the crossover frequency of the whole control system is always set to be in the medium band, typically with a value of $f_{sw}/10$, where f_{sw} means the switching frequency [12]. In order to fulfill this requirement, k_{p_PR} cannot be set to a great value. As will be analyzed below, the value is too small to assure that the open-loop gain of the control system stay in the upper half plane in the low frequency band. Obviously, this will result in instability. That is to say, single current regulator of PR controller cannot meet the stability demand of control system.

In order to increase the gain in the low frequency band, an additional PI controller is used in this paper. The controller is in the following form.

$$G_{PI}(s) = k_{p\_PI} + \frac{k_i}{s} \quad (9)$$

This controller has the advantage of infinite gain in zero frequency and fixed gain in high frequency band. Thus, it is easy to use the controller to not only enlarge the system gain in low band, but also avoid its influence to the crossover frequency. The integral ratio k_i should also be carefully chosen to avoid the -90° phase shift in low frequency band undermine the phase margin of the whole system. As a result, the current controller and the open-loop transfer function of the whole system can be described, respectively, as

$$G_i(s) = G_{PR}(s)G_{PI}(s) \quad (10)$$

$$G_t(s) = G_{PR}(s)G_{PI}(s)G_2(s) \quad (11)$$

IV. EXPERIMENTAL RESULTS

To validate the proposed active grounding system practically, a prototype is built in laboratory, based on the same parameters in TABLE I. The neutral point in Fig. 1 is realized by a Zigzag grounding transformer. The inherent phase-to-ground capacitance and resistance is realized by two groups of capacitors and resistors corresponding to nominal value in TABLE I and 30% of them to represent two different load levels. The control methods discussed above are executed in a digital signal processor TMS320F28335 development platform with carrier waveform frequency of 10 kHz. In the experimental process, a step-up of load from 30% to 100% nominal load is carried out. Dynamic waveforms subjecting to the two step-ups with different controllers are shown in Fig. 9.

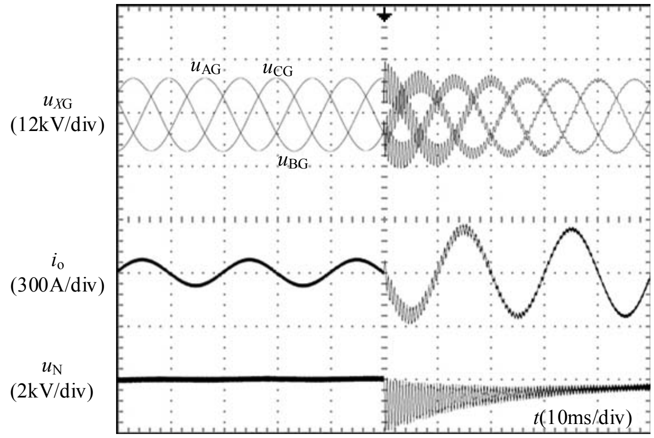

Fig. 9 Dynamic waveforms subjecting to load step-up from 30% nominal load to 100% with proposed method

TABLE I
System parameters

Elements	Parameters	Values
Distribution Network	Damping ratio d	0.08
	Phase-to-ground capacitance C_A, C_B	8.76uF
	Phase-to-ground capacitance C_C	14uF
	Phase-to-neutral voltage E_X	10.5/√3kV
Grounding system	Transformer ratio	10.5/√3:0.32
	Output inductance L_o	0.5mH
	Output capacitance C_o	50uF
	Inverter gain K_{pwm}	300
	DC voltage	600V

It can be seen from Fig. 9 that with the proposed controller, the voltages are balanced before and after load step-up, which indicates the proposed controller is more suitable for different load levels than PI controller. It should be noticed that the dynamic processes of neutral-to-ground voltage after the load change are longer than that of output current, due to the large time constant of the load.

V. CONCLUSION

Active grounding system is able to effectively restrain the neutral-to-ground voltage to avoid possible overvoltage caused by asymmetrical inherent phase-to-ground parameters or resonance between Petersen coil and phase-to-ground capacitance. Current control method of the system is presented which consists of a PR plus PI controller and capacitive current feedback. The proposed control method is suitable for large range of load change and is immune to possible resonance of load capacitance and the inductance of output LC filter. Experimental results show the proposed control method has good performance in dynamic and steady state.

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