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A flexible control strategy with overcurrent limitation in distributed generation systems

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ABSTRACT

Distributed Generation (DG) systems are typically interfaced with distribution lines by modern power converter devices, which their controllers and dynamic behaviours are significantly influenced by unbalanced grid faults. The active and reactive power control with positive-negative sequences (PNS) is one of fundamental of power converter control under grid fault conditions. This paper proposes a reference current generator (RCG) based flexible power control strategy to enable regulation of active and reactive power with minimizing active and reactive power oscillations. Current limitation control is embedded into the RCG in order to keep maximum current injection in safety limitation for overcurrent protection under grid faults and harmonic distortions. The proposed control strategy has been also accomplished maximum active power and minimum reactive power transfer capability to electric grid. The analytical expression of active and reactive power oscillations depending on flexible control parameters are comprehensively investigated as theoretically and examined with simulations. Fractional order proportional integral (FOPI) controller is preferred to minimise steady state error of AC current regulation and provide faster processing time instead of conventional PI and proportional resonant (PR) controllers. An important contribution for similar previous studies is that PNS voltage and current components are separated by dual average filter based phase locked loop (DAPLL) which is firstly proposed in this paper. The performance of proposed controller is compared with multiple complex-coefficients filter (MCCF-PLL) based controller. Theoretical analysis and simulation results verify the correctness and effectiveness of the proposed solution.

1. Introduction

Distributed generation (DG) power systems technologies and alternative energy sources appear to be a viable option for addressing the increased demand for electricity which are directly connected to the consumers' load or dispatched to electric grid with power electronic devices at the low, medium and high voltage [1–4]. In order to maintain a stable power system in the interconnection DG power systems and transmission system operators, the impact of grid disturbances on the control of DG power systems need to be investigated [5,6]. The conventional control methods are mainly suitable for grid connected inverters (GCIs) under balanced conditions. However, electric grid voltage is affected by many factors such as overloads, grid faults and start-up of motors [7]. Therefore, the dynamic behaviour and control of the GCI can considerably influenced by unbalanced grid conditions. The GCI can exhibit undesirable performance such as overcurrent, power oscillations and DC bus voltage oscillations during grid faults [8].

Some recent studies have been analysed the flexible control algorithms for the impact of grid faults on control of the GCI. While some researchers focused on excessive current stresses, the other researchers studied on maximum power delivery at rated inverter power capacity in [9–18]. Hence, the various reference current generators (RCGs) or reference power generators are presented to control the GCI for overcurrent prevention or maximum power delivery capability under grid fault conditions. In [9,11], the RCG based control algorithms have been developed for regulation of active and reactive powers. The analytic relationship between control parameters of positive–negative sequences (PNS) with power oscillations is well discussed and analysed. The overcurrent is achieved within safe current operation range. However, maximum injected current exceeds rated current in [10,11] because to avoid overcurrent phenomenon under grid faults, maximum injected current should be limited to rated current. The impact of harmonic distortions is not also considered. In [12], an advanced control algorithm is reported that peak current limitation is achieved by limited active power in wind turbine. Other interesting power control method is reported that a new vector transformation based

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instantaneous p-q power control is enhanced in [13]. The system dynamics are considerably limited due to more computational burden and using more control modules in these methods. Moreover, conventional controllers such as proportional integral (PI) and proportional resonant (PR) controller are used for AC current regulation [9,14–17]. In particular, the impacts of harmonic distortions and voltage unbalanced factor are not taken into consideration in these control algorithms. The paper [18] offers sliding mode and Lyapunov function based control strategy. Active and reactive power oscillations are regulated and impacts of negative sequences are reported. However, current limitations are not surpassed and flexible control is not taken into consideration.

The sequences extractors are considerably essential control module to obtain the RCG. In addition, they are required to achieve accurate and fast dynamic behavior of GCI under grid faults and harmonic distortions. Some researchers have been reported various PLL based PNS extractors to generate reference current in the literature. Dual second-order generalized integrator (DSOGI) [15,19], time delay based PLL [20], third order sinusoidal integrator (TOSSI) [21] and multivariable based PLL (MVF) [14] are presented for detection of PNS components in stationary reference frame (STRF) and double synchronous reference frame (DSRF) [22], decoupled double synchronous reference frame (DDSRF) [23], differentiator method [24] are also presented for separation of PNS in synchronous reference frame (SRF) under unbalanced conditions. These methods are easily affected by voltage harmonic and some part of them has more the computational burden for signal processing. The speed of detection PNS components is slower. Moreover, using multiple filters increase the complexity of the control algorithm. The paper [25] only extracts positive sequences to generate reference current. The impacts of negative sequences on control signals and power oscillating components were not taken into account. In [26], multi complex coefficient filters (MCCF) based PNS extractor is presented to obtain fast and accurate PNS components. However, the impact of voltage harmonics, including many sub-modules and computational burden still seem problems. Among the above mentioned methods, DSC-PLL and MVF-PLL has the lowest dynamic response. On the other hand, the DSOGI provides much simpler structure for PNS extractor, but relatively slower response than proposed PLL. The MCCF-PLL has the transient response comparable with the TOSSI-PLL and DDSRF.

In this paper, the RCG based flexible control strategy has been carried out regulation of active and reactive powers with minimizing active and reactive power oscillations in GCI interfaced DG system under grid faults and harmonic distortions. The maximum current limitation control is inserted to the RCG for overcurrent protection. The impact of flexible control parameters on amplitudes of active and reactive power oscillations are examined and compared with MCCFF-PLL based RCG control strategy. Performance comparison of proposed control strategy is also comprehensively tested and reviewed with some previous studies. Fractional Order PI (FOPI) controller is used to achieve fast and accurate AC current regulation at steady state error instead of PI and PR controllers. Another key novelty is that PNS voltage-current components for the RCG are measured by proposed fast and robust dual average filter based PLL (DAPLL). The oscillations caused by grid faults and voltage harmonics on PNS orthogonal (d-q) signals are removed by proposed DAPLL. This paper provides some advantages in fourfold: (1) the PNS voltage-current components are separated by improved DAPLL, which provides fast response time, good robustness under grid faults and is not affected by low and high order harmonic components, (2) maximum active power and minimum reactive power are injected into utility grid without exceeding allowable phase current, (3) the proposed RCG based control algorithm is capable to deal with overcurrent limitation and (4) the analytical expression of active and reactive power oscillations based on flexible control parameters are comprehensively investigated as theoretically and verified with numerical and simulations results. Various cases are presented to support the validity and effectiveness of the proposed control strategy.

This paper is organized as six sections. Following the introduction section, the active and reactive power oscillation are formulated and analysed. In Section 3, the proposed flexible phenomenon based overcurrent limitation control and constant power control are introduced. In Section 4, proposed system is presented with PNS extractors and AC current regulation controller. Simulation results in Section 5 corroborate the claimed features of proposed solution. Performance comparison of proposed control strategy is discussed in Section 6. Section 7 concludes the paper and summarizes its main contribution.

2. The problem formulation with instantaneous power theory

Instantaneous active and reactive powers p, q are given in Eq. (1) [14];

$$p = v.\, i = v_a i_a + v_b i_b + v_c i_c$$
$$q = v_{\perp}.\, i = \frac{1}{\sqrt{3}}(v_b - v_c)i_a + (v_c - v_a)i_b + (v_a - v_b)i_c \tag{1}$$

where "⊥" denotes a vector derived from matrix transformation. v and $v_{\perp}$ are orthogonal each other. Zero sequence components may be disregarded because θ of three wire structure. Three phase unbalanced grid voltage signals based on PNS components are written in matrix form.

$$v = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = \begin{bmatrix} v^+\sin(\theta^+) + v^-\sin(\theta^-) \\ v^+\sin(\theta^+ - 2\pi/3) + v^-\sin(\theta^- - 2\pi/3) \\ v^+\sin(\theta^+ + 2\pi/3) + v^-\sin(\theta^- + 2\pi/3) \end{bmatrix} \tag{2}$$

where positive phase angle θ^+ is equal to θ, which is measured from proposed PLL and negative phase angle θ^- equal to $-\theta$.

$$v_{\perp} = \frac{1}{\sqrt{3}}\begin{bmatrix} 0 & 1 & -1 \\ -1 & 0 & 1 \\ 1 & -1 & 0 \end{bmatrix} v \tag{3}$$

Considering three phase unbalanced grid voltage and currents, the active and reactive powers are written based on PNS components. Letters p, q are related to active and reactive power controls, which consist of active and reactive power oscillations, respectively.

$$p = v.\, i = (v^+ + v^-)(i^+ + i^-)$$
$$q = v_{\perp}.\, i = (v_{\perp}^+ + v_{\perp}^-)(i^+ + i^-) \tag{4}$$

Reformulated Eq. (4) in terms of $i_d^{\pm}$ and $i_q^{\pm}$.

$$p = (v^+ + v^-)(i_d^+ + i_q^+ + i_d^- + i_q^-) = \underbrace{(v^+ i_d^+ + v^+ i_q^+ + v^- i_d^- + v^- i_q^-)}_{P} + \underbrace{(v^+ i_d^- + v^- i_d^+ + v^+ i_q^- + v^- i_q^+)}_{p_{2w}} \tag{5}$$

$$q = (v_{\perp}^+ + v_{\perp}^-)(i_d^+ + i_q^+ + i_d^+ + i_q^+) = \underbrace{(v_{\perp}^+ i_d^+ + v_{\perp}^+ i_q^+ + v_{\perp}^- i_d^- + v_{\perp}^+ i_q^+)}_{Q} + \underbrace{(v_{\perp}^+ i_d^- + v_{\perp}^- i_d^+ + v_{\perp}^+ i_q^- + v_{\perp}^- i_q^+)}_{q_{2w}} \tag{6}$$

where $v = v^+ + v^-$, $v_{\perp} = v_{\perp}^+ + v_{\perp}^-$, $v^+ = v_d^+ + v_q^+$ and $v^- = v_d^- + v_q^-$, similarly, for PNS current signals $i^+ = i_d^+ + i_q^+$ and $i^- = i_d^- + i_q^-$. p_{2w} and q_{2w} represent active and reactive power oscillations. From Eqs. (5) and (6) can be divided into two parts: one part is average power without oscillations, another part is active and reactive power oscillations. The detailed of power oscillations are given subsection in following.

2.1. Analysis of active-reactive power oscillations

Average active power P is obtained by Eqs. (4) and (5) under balanced conditions.

$$P = v^+ i^+ + v^- i^- \tag{7}$$

The active power oscillations are adjustable with flexible control