Full Length Article

Modified SOGI based shunt active power filter to tackle various grid voltage abnormalities

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ABSTRACT

Shunt Active Power Filters (SAPF) have been effectively used to compensate the harmonics generated by the non-linear loads. The SAPF's performance depends on the accurate generation of reference current, which is dependent greatly on the template of supply voltage. When the grid voltage (or its template) is characterized by different abnormalities like presence of harmonics, imbalance, dc-offset etc., some of the conventional techniques of frequency estimation may fail to correctly estimate the frequency. This ultimately affects the reference current generation and hence, the SAPF operation, ultimately leading to high distortion of the grid currents. The paper presents modified dual second-order generalized integrator (MDSOGI) based SAPF to ensure effective compensation of harmonics, even when the grid voltage is characterized by all the abnormalities mentioned above. It is highlighted with one case that when the sensed voltage is having dc-offset, DSOGI-SAPF results into the source current with THD, dc-offset and harmonic with values 5.82%, 0.8% and 4.5%, respectively. For the same case, the proposed technique yields grid current which is free of dc-offset and 2nd harmonic and has THD = 3.57%. The dynamic performance of the MDSOGI-SAPF is validated and its superior performance over DSOGI-SAPF is illustrated even with experimental results.

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1. Introduction

The concern about the generation of harmonic components due to increased use of power electronics based application in modern power systems have been widely discussed. The penetration of these harmonic current signals generated by the nonlinear loads and other power-electronics equipment into the electrical utility leads to power losses, heating of electrical equipment, saturation of magnetic components, supply voltage distortion at the point of interface, mal-operation of protective devices, etc. Traditionally, passive filters were very popular to limit the injection of harmonics into the utility. However, to deal with the harmonics, the power electronic converters known as active power filter (APF) is an attractive alternative to passive filters [1–4], as they are smaller, fast, free from problem of resonance, and adaptive in nature.

APFs can be categorized as shunt, series or hybrid filters. Of these, the shunt APF (SAPF) configuration is the most popular solution [5–9]. The performance of the SAPF is greatly dependent on how precisely the reference compensating current is computed. The task of generating this reference compensation current is challenging, especially when the system operates in a weak grid or micro-grid, which is very likely to have distorted supply voltage, harmonics, unbalanced load, imbalance in supply voltage etc [8–13]. Under such case for computing reference compensation current, it is must to compute the fundamental positive sequence components (PSCs) of grid voltage accurately. The accuracy of the fundamental PSCs depends on the accurate information derived about the phase, frequency and amplitude of grid voltage.

Various phase/frequency estimation techniques, which can be broadly categorized as frequency domain (FD) and time domain (TD) techniques, have been reported in literature. The FD techniques based on discrete Fourier transform (DFT) have good precision in detecting different harmonics.
and require more memory. The computational burden is also increased under distorted grid signal [14]. To reduce complexity in computation and implementation, recursive discrete Fourier transform (RDFT) and sliding window discrete Fourier transform (SDFT) are suggested in [15]. However, due to variable sampling rate, these methods have issues like higher steady state error and instability. These drawbacks are further investigated in [16], where improved SDFT algorithm is presented to deal with the issue. However, it takes at least five cycles to estimate the fundamental frequency of grid signal under various grid abnormalities.

Compared to the FD approaches, the closed loop TD approach based on phase-locked loop (PLL) offers several advantages like simplicity, better capability of disturbance rejection, low sensitivity to the variations and distortion in grid voltage etc. Further, it has higher accuracy and offers relatively more stable and reliable performance. The performance of the TD technique depends on the type of PLL which further is greatly influenced by the configuration of phase detector (PD) structure it employs. The power-based PLL (p-PLL) employing sinusoidal multiplier as PD is the simplest closed-loop PLL. Unfortunately, it suffers with the double frequency oscillation in the estimated parameters. Various modifications have been suggested to overcome aforesaid drawbacks of p-PLL [17,18]. Orthogonal-signal-generation (OSG) based PD in which a fictitious orthogonal signal is generated from the original single-phase signal is also reported to effectively overcome the issue of double-frequency oscillation. However the performance is sensitive to distorted grid voltage conditions. The classification of PLL based on the different phasedetectors is reported in [19]. Their performance is evaluated under different grid severity for a single-phase system. The PD structure based on generalized integrator (GI) is an attractive solution to accurately estimate phase/frequency. However, in case of non-sinusoidal input signals and varying frequency conditions it results into erroneous performance [19]. Unlike it, the second-order GI based PLL (SOGI-PLL) shows accurate performance with the distorted input signals and is even suitable for variable frequency applications. To compute the frequency, the SOGI-PLL continuously utilizes the estimated frequency as a feedback for SOGI block. Unlike it, the frequency-locked loop (FLL) adaptively obtains the frequency information avoiding the need of PLL. It further improves the response [19–21]. The performance can further be improved by employing dual SOGI-PLL (DSOGI-PLL) for three-phase application, resulting into better transient response and stability in the presence of grid abnormalities. However, if input signal has the dc-offset error, the estimated frequency with DSOGI-PLL is characterized by the oscillatory response. The presence of the dc-offset in input signal may be due to erroneous A/D conversion processor, measuring instruments or due to half wave converters, dc insertion from distributed generation etc. [22–24]. Band pass filter (BPF) can be introduced before the PLL input to tackle the dc-offset present in input signal as suggested in [25]. It rejects the dc-offset effectively at the cost of slowing down the response. In [26], the performance of in-loop filtering approach is explained, which employs $dq$-delayed-signal-cancellation ($dq$-DSC) and a notch filter is compared with that of preprocessing tools like $zq$-DSC, complex coefficient filters and cross-feedback network. The detail study shows that the in-loop filtering has more undesirable effect on the performance of the PLL than the preprocessing tools. Therefore in-loop filtering is less advisable than the pre-filtering approaches [27]. To filter the dc-offset before the PLL input, adaptive notch filter (ANF) realized by some alterations in the SOGI-FLL structure, is reported in [28] for a single-phase system. The ANF as a pre-filtering tool helps in the correct estimation of frequency even when the dc-offset is present. Three such ANFs are required for three-phase systems [28]. Similar performance can be achieved by employing modified DSOGI-PLL (MDSOGI-PLL) [29]. The accuracy with which the frequency is estimated affects the performance of the power electronic converters.

In this paper, performance of MDSOGI-PLL based SAPF is evaluated under grid-voltage abnormalities like, supply voltage imbalance and dc-offset. The MDSOGI-PLL presented in the paper employs just two modified SOGI (MSOGI) structure for the accurate estimation of the frequency and hence, the effective operation of the SAPF. The system configuration of MDSOGI-PLL based SAPF, detailed analysis and the simulation and experimental results are included in later sections.

### 2. System configuration

Fig. 1 shows the system configuration of the MDSOGI-PLL based SAPF, which is connected at the point of common coupling (PCC) to supply the harmonics generated by the non-linear load. As a non-linear load, a three phase uncontrolled rectifier feeding a resistive

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
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<tbody>
<tr>
<td>$v_{sa}, v_{sb}, v_{sc}$</td>
<td>instantaneous phase voltages at input terminals of utility, V</td>
<td></td>
</tr>
<tr>
<td>$i_{sa}, i_{sb}, i_{sc}$</td>
<td>instantaneous line currents at input terminals of utility, A</td>
<td></td>
</tr>
<tr>
<td>$i_{La}, i_{Lb}, i_{Lc}$</td>
<td>instantaneous load currents at PCC, A</td>
<td></td>
</tr>
<tr>
<td>$V_{sa}, V_{sb}, V_{sc}$</td>
<td>instantaneous compensating currents at PCC, A</td>
<td></td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>dc-offset in supply voltage, V</td>
<td></td>
</tr>
<tr>
<td>$k_1$</td>
<td>SOGI-OSG gain</td>
<td></td>
</tr>
<tr>
<td>$V_m$</td>
<td>amplitude of input voltage, V</td>
<td></td>
</tr>
<tr>
<td>$R_L$</td>
<td>load resistance, $\Omega$</td>
<td></td>
</tr>
<tr>
<td>$V_{dc}$</td>
<td>dc-link voltage, V</td>
<td></td>
</tr>
<tr>
<td>$k_{dc}$</td>
<td>dc-loop gain</td>
<td></td>
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<tr>
<td>$\gamma$</td>
<td>FLL loop gain</td>
<td></td>
</tr>
<tr>
<td>$L_f$</td>
<td>Filter inductance connected at PCC, mH</td>
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