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Harmonic analysis of hybrid renewable microgrids comprising optimal design of passive filters and uncertainties

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ABSTRACT

In this paper, the applications of passive filters in grid-connected and isolated hybrid renewable microgrid are addressed. The single-tuned filters are engaged to reduce the total harmonic distortion (THD) at the point of common connection with keeping total demand distortions below the maximum allowable limits. The total cost of proposed passive filters along with THD define the adapted bi-objectives to be minimized simultaneously provided that set of operating inequality constraints are satisfied. A multi-objective grasshopper optimization algorithm (MOGOA) is applied in this regard. The best answers are picked up carefully among the Pareto solutions by technique for order of preference by similarity to ideal solution (TOPSIS) procedures. Harmonic analysis is performed to examine the critical frequencies in many instants before and after installing passive filters. The effects of harmonics on the motor and wind generator torques are analysed and discussed. In addition, the system power factor is improved. Various scenarios regarding the operations of the grid under study are investigated comprising uncertainties of renewable power sources. The reductions in torque ripples of induction motor and wind turbine generator are indicated. It can be emphasized that the cropped results of filter's cost along with THD generated by MOGOA are very competitive and convincing when they are compared to the results of the well-structure multi-objective genetic algorithm.

1. Introduction

Power quality of power systems receives special attentions by customers, industries and utilities to have an acceptable sine waveform at a constant frequency [1–4]. Advancement in technologies have been established in case of conventional and non-conventional energy sources (i.e. wind power, solar power, and etc.). In many countries, the power grids collect power generated from multiple sources (both conventional and renewables) which requires carefully quality control schemes by official regulations. Harmonic distortion arises as a result of the combination of nonlinear elements in the electric power systems due to the intensive usage of power semi-conductor technologies [1,3].

Many consequences can be raised due to the high level of harmonics, alternatively, called total harmonic distortion (THD). Based on IEEE Std 519-2014, if the level of THD exceeds 8% at the point of common connection (PCC) at low voltage levels, the system should be investigated. In addition, an appropriate action to maintain the levels of THD within an acceptable limits is essential [3]. Many solutions to mitigate the level of harmonics are proposed. Among them, harmonic filters, phase multiplication, special designed transformer, compliance to harmonic standards, appropriate earthing design and etc. [1,3,5–24].

A method for sizing passive filters for time-varying nonlinear loads is realized by using a minimization technique [25]. In the last decade, researchers have proposed to apply modern optimization approaches to allocate harmonic filters along power networks such as genetic algorithms (GAs) [26–28], a graph search algorithm [29], game theory concepts [30], particle swarm optimizers [31], simulated annealing [32], differential evolution [33] and many more [34–36]. In Ref. [26], GA-based approach for optimal design of passive LC filter has been presented. The objective is to realize the maximum power factor (PF). Another application of the GA is addressed in Ref. [27] to estimate the R–L–C parameters. The objective is adapted to minimize the harmonic impedance and to maximize the fundamental frequency impedance aiming to reduce network losses. The readers are invited to refer to the comprehensive literature which can be found in Ref. [19].

It can be concluded from the aforementioned survey that few attentions are paid for optimizing the sizing of harmonic filters to have a compromise solution between many factors such as total filter cost, PF, THD and system energy savings. Grasshopper optimization algorithm (GOA) is recently developed as an alternative challenging optimization technique [37].

GOA, as an efficient optimization technique, is inspired form the life

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style (movement, migration) of grasshopper in natural. The adult insects of grasshopper travelling together over long distance which mimics exploration of optimization technique. The nymphs have no wing so it moves in small area which mimics the exploitation of optimization technique [37]. GOA has been proven to be competitive when it compared to well-established competing algorithms with lesser number of controlling parameters [37,38]. Recently, a multi-objective GOA (MOGOA) is developed in 2017 [39].

The current paper presents a comprehensive novel application of the MOGOA-based on methodology to size the passive filters (optimally) to suppress the harmonics along hybrid renewable microgrids (grid-connected and autonomous modes). A non-linear optimization problem is adapted to realize the optimal values of filter elements subjects to set of operating inequality constraints. MATLAB/SIMULINK is used to perform such numerical simulations. The well-known multiobjective GA (MOGA) is engaged to validate and appraise the results obtained by the MOGOA. The procedures of technique for order of preference by similarity to ideal solution (TOPSIS) are used to pick up the best compromise solution among the set of Pareto-front optimal (PFO) solutions. The used passive filters have dual purposes: (1) improve the power factor, and (2) suppress the harmonics. Various scenarios are analysed and discussed including the observations of machines torque ripples.

The major contributions of the current research are: (i) application of MOGOA to solve passive filter design problem, (ii) optimal passive filter design and solving for practical study cases related to microgrid and in coordination with valid power quality international standards, (iii) best compromise is picked carefully by using TOPSIS procedures, (iv) observations of torque ripples in wind turbine (WT) and induction motor (IM) with and without filters are reflected, and (v) finally, uncertainties of renewable power sources for realistic analysis are investigated.

The remaining of this manuscript is structured as follows: Section 2 presents an overview of harmonic filters. In Section 3, the problem representation with its associated constraints are addressed. Section 4, reveals the procedures of the MOGOA to the proposed work. In Section 5, detailed description of the system under study is framed along with the data sheets of the system's elements which are given in Appendix A. Section 6, numerical simulations and the best results obtained by MOGOA in comparisons to MOGA are presented and discussed. At last, the framework and future extension of this current work is given in Section 7.

2. Overview of harmonic filters

The harmonic filters are categorized into the following types [1,19,40,41]: (i) passive filters, (ii) active filters, and (iii) combination of them. Passive filters are characterized as a resonant circuit with a low impedance at its tuned frequency to be trapped. Passive filters can be connected in series or in shunt or in combination of series/parallel [1]. Although these types of filters have number of drawbacks, the industry chooses them as favourite solutions to suppress the harmonic pollutions for the reasons that they are very common and economical [40,41]. On the other hand, it is well-known that the types of active filters inject harmonics at 180° out of phase with the load harmonics [40]. In spite of the advantages of such active filters, the fast switching of high currents in the active filters may cause electromagnetic interferences in the power distribution systems and have many claims from industries [40]. In addition, the technology of these types of filters still requires further researching and development. Nevertheless, detailed comparisons between the passive and active filters are outlined in Ref. [40].

In a common practice, the passive filters are tuned at frequencies with tolerant values ± 3% to ± 15% far from the harmonic frequencies anticipated for suppressions [1]. The later mentioned as a result of the ratings of inductors and capacitors may change due to manufacture tolerances [1,4,5] (typically ± 8% and ± 5% tolerances in capacitance and inductance; respectively, which are sufficed for harmonic filtering purpose). The general formula to express this alteration is depicted in Eq. (1).

$$F_{tuned} = \frac{F_{harmonic}}{\sqrt{(1 \pm \tau_C)(1 \pm \tau_R)}} \quad (1)$$

where F_{tuned} is the actual tuned frequency, $F_{harmonic}$ is the specified harmonic frequency to be suppressed, τ_C is the capacitor manufacture tolerance and τ_R is the reactor tolerance.

The value of order to which the filter is tuned (h_{tuned}) is defined by using Eq. (2).

$$h_{tuned} = \frac{F_{tuned}}{F_{harmonic}} \quad (2)$$

The harmonic filters introduce a very low impedance (of course at resonance) path to the harmonics of the system. The current work cares by shunt passive filters and in particular using single-tuned filters (STFs).

The effective reactive power (Q_{eff}) and effective reactance (X_{eff}) of the harmonic filter in the net reactive power of inductive and capacitive elements are computed using Eqs. (3) and (4); respectively [1,3].

$$Q_{eff} = Q_C - Q_L \quad (3)$$

$$X_{eff} = X_C - X_L = \frac{V_L^2}{Q_{eff}} \quad (4)$$

where Q_C and Q_L are the capacitive and inductive reactive powers; respectively, X_C and X_L are the capacitive and inductive reactance at fundamental frequency; respectively, and V_L is the system line–line voltage.

3. Problem formulation

Total demand distortion (TDD) provides good indication regarding how big influence of harmonic distortion on the system under various loading conditions. TDD is computed using the formula revealed in Eq. (5) [3]. However, the voltage THD_V and current THD_I can calculated using Eq. (6) [3,19]. Quite the opposite of THD_I (referred to fundamental current), very high TDD levels may possibly be noticed under low loading conditions, which apparently indicates big impact of harmonics. On the contrast to that, in this said case the impact on the system is low.

$$TDD = \frac{1}{I_{Load}} \times \sqrt{\sum_{h=2}^{N} I_h^2} \quad (5)$$

where I_{Load} is the maximum demand load current at fundamental frequency, I_h defines the harmonic current and N is the number of harmonics.

$$THD_V = \frac{1}{V_1} \times \sqrt{\sum_{h=2}^{N} V_h^2}, \quad THD_I = \frac{1}{I_1} \times \sqrt{\sum_{h=2}^{N} I_h^2} \quad (6)$$

where V_1 defines the fundamental voltage, I_1 denotes the fundamental current and V_h defines the harmonic voltage.

The cost of passive filters is computed using formula shown in Eq. (7).

$$TC = K_{SC}.\ Q_{SC} + K_C.\ \sum_{i=1}^{N_f} Q_{Ci} + K_L.\ \sum_{i=1}^{N_f} Q_{Li} + K_R.\ \sum_{i=1}^{N_f} P_{Ri} \quad (7)$$

where K_{SC} is the unit cost of a switched capacitor ($/kVAr), K_C is the unit cost of filter capacitor ($/kVAr), K_L is the unit cost of filter inductor ($/kVAr), K_R is the unit cost of filter resistor ($/kW), Q_{SC} defines the kVAr size of a switched capacitor, Q_{Ci} and Q_{Li} represent the amount of capacitive and inductive in kVARs of i-th filter branch; respectively, P_{Ri} denotes total real power of i-th filter branch, and N_f is the number of filter branches.