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Intelligent fuzzy-based reactive power compensation of an isolated hybrid power system

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ABSTRACT

In this paper, an isolated wind-diesel hybrid power system model is considered for its on-line reactive power compensation. In the studied power system model, a diesel engine based synchronous generator (SG) and a wind turbine based induction generator (IG) are used for power generation. IG offers many advantages over the SG but it requires reactive power support for its operation. So, there is a gap between the reactive power demand and its supply. To minimize this gap between reactive power generation and its demand, variable source of reactive power such as static VAR compensator (SVC) is used. The different tunable parameters of the studied hybrid power system model are optimized by a novel opposition-based gravitational search algorithm (OGSA). Gravitational search algorithm (GSA) is based on the law of gravity and the interaction between the masses. In GSA, the searcher agents are a collection of masses and their interactions are based on the Newtonian laws of gravity and motion. To further improve the optimization performance of the GSA, opposition-based learning is employed for population initialization and also for generation jumping. The performance analysis of a Sugeno fuzzy logic (SFL) based controller for the studied isolated hybrid power system model is also carried out which tracks the degree of reactive power compensation for any sort of input perturbation in real-time. Time-domain simulation of the investigated power system model reveals that the proposed OGSA-SFL yields on-line, off-nominal optimal SVC parameters resulting in on-line optimal terminal voltage response.

1. Introduction

The main advantages of using renewable energy sources are that these are clean in nature, sustainable and eco-friendly. In modern power system, there has been a continuous enhancement of power generation from renewable energy sources like solar energy and wind energy. Wind energy is intermittent and fluctuating in nature. Thus, power generation from wind is variable. To reduce this fluctuation of wind generation, wind power generations are, generally, designed to operate in parallel with diesel generators [1]. This combination of diesel and wind energy system is known as wind-diesel hybrid power system [2–4].

Different renewable sources such as wind and mini/micro hydro is available at different geographical locations, close to loads. Therefore, the latest trend is to have a distributed or dispersed power system [5–7]. Examples of such are wind-diesel, wind-diesel-microhydro system, etc. These systems are known as isolated hybrid power system.

Thus, in general, there may be more than one type of electrical generators in any hybrid energy system [8]. In such circumstances, it is normal although not essential for diesel engine based generator(s), usually, to be synchronous generator (SG) and wind-turbine based generator(s) to be asynchronous such as induction generator (IG). An IG offers many advantages over the conventional SG as a source of isolated power supply. Reduction in unit cost, ruggedness, absence of brushes (in squirrel cage construction), absence of separate DC source for excitation, easy maintenance, self protection against severe overloads and short circuits, etc. are the main advantages of an IG [9–12] but it requires reactive power support for its operation. Due to this mismatch between generation and consumption of reactive powers, more voltage fluctuations occur at generator terminal in an isolated system which reduces the stability and quality of supply. The problem becomes more complicated in hybrid system having both IGs and SGs. In the present investigated hybrid power system model, SG and IG are chosen with diesel generator and wind turbine, respectively. The maximum efficiency may be achieved by using the full reactive power capability of the wind system for decreasing the system losses and improving the post-fault voltage profile.

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List of symbols

$B_c = \omega C$	susceptance of the fixed capacitor
$B_l = 1/\omega L$	susceptance of the fixed reactor
B_{svc}	equivalent susceptance of the SVC
E_{ss}	steady-state error
FOD	Figure of demerit (a time-domain performance index)
K_a	exciter gain
K_v	gain of energy balance loop
M_p	overshoot
t_r	rising time, s
t_s	settling time, s
T_a	exciter time constant, s
T'_{do}	direct-axis open circuit transient time constant, s
T_r	voltage transducer time constant, s
T_v	time constant of energy balance loop, s
X_d	direct-axis reactance of synchronous generator under steady state condition, p.u.
X'_d	direct-axis reactance of synchronous generator under transient state condition, p.u.
ΔE_{fd}	incremental change in exciter voltage, p.u.
ΔE_q	incremental change in internal armature emf under steady state, p.u.
ΔP_{ig}, ΔQ_{ig}	incremental changes in active and reactive powers of induction generator, respectively, p.u.
ΔP_{load}, ΔQ_{load}	incremental changes in active and reactive powers of load, respectively, p.u.
ΔP_{sg}, ΔQ_{sg}	incremental changes in active and reactive powers of synchronous generator, respectively, p.u.
ΔQ_{svc}	incremental change in reactive power of static VAR compensator, p.u.
ΔT_e	incremental change in electromagnetic torque, p.u.
ΔT_m	incremental change in mechanical torque, p.u.
ΔV	incremental change in load voltage, p.u.
ΔV_{ref}	incremental change in reference voltage, p.u.
ΔV_t	incremental change in terminal voltage, p.u.
$\Delta \omega_r$	incremental change in rotor speed, p.u.

Various flexible AC transmission system (FACTS) devices are available which can supply fast and continuous reactive power support [13–16]. For standalone applications, effective capacitive VAR controller has become central to the success of IG system. Switched capacitors, static VAR compensator (SVC) and static synchronous compensator may provide the requisite amount of reactive power support. A switched capacitor scheme is cheaper but it regulates the terminal voltage in discrete steps. The primary purpose of SVC is to regulate the voltage of the transmission systems. In a stand-alone hybrid power system, the reactive power device has to fulfill the variable reactive-power requirements for the operation of the IG and that of the load. In the absence of proper reactive power support and its proper controls, the system may be subjected to large voltage fluctuations, which is not desirable. In the present work, SVC is considered for the purpose of requisite reactive power support.

Various types of SVC controllers have been proposed in the literature like lead–lag controllers [17,18], proportional-controllers [19,20], proportional–integral controllers [21,22] and proportional–integral–derivative (PID) controllers [16]. Generally, the parameters of an SVC controller are selected on the basis of a typical load but these values may not be optimum for different voltage characteristics. Therefore, the parameters of the SVC controllers require proper tuning to always have optimum settings for variations in the load voltage characteristics with load. The constant impedance model is not accurate and is not the proper approximation in view of the strong influence of load voltage sensitivity on the dynamic performance of the power system [23–26]. The SVC damping controller designed under constant impedance model may become unstable under other values of loads.

Rashedi et al. proposed gravitational search algorithm (GSA) in [27]. It is a heuristic evolutionary optimization algorithm based on the metaphor of gravitational interactions between masses. GSA is inspired by the Newton theory that postulates every particle in the universe attracts every other particle with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

Tizhoosh introduced the concept of *opposition-based learning* (OBL) in [28]. The main idea behind the OBL is the simultaneous consideration of an estimate and its corresponding opposite estimate (i.e., guess and opposite guess) in order to achieve a better approximation for the current candidate solution. In the recent literature, the concept of opposite number has been utilized to speed up the convergence rate of an optimization algorithm such as opposition-based differential evolution [29]. In the present work, the same idea of opposite number is blended with GSA for population initialization and also for generating new population. The optimization approach utilized in the present work has been called as opposition-based GSA (OGSA).

A Sugeno fuzzy logic (SFL) based controller may adjust its parameters on-line according to the environment in which it works and may provide a good damping over a wide range of operating conditions. Sugeno fuzzy controller for on-line tuning of power system stabilizer (PSS) controller has been adopted in [30]. Off-line conditions are sets of nominal system operating conditions which is given in the SFL table. On the other hand, these input operating conditions vary, dynamically, in real-time environment and become off-nominal. This necessitates the use of very fast acting SFL to determine the off-nominal controller parameters for off-nominal input operating conditions occurring in real-time.

In view of the above, the major contributions of the present work are as follows:

(a) Reactive power compensation of an isolated hybrid power system model is carried out with the help of SVC.
(b) The different tunable parameters of the hybrid power system model are optimized with the help of OGSA, developed by the authors.
(c) The terminal voltage response profile of the studied hybrid power system model is plotted, compared and analyzed.
(d) The optimal terminal voltage responses and the convergence profiles yielded by the OGSA are compared to those yielded by the basic GSA, particle swarm optimization (PSO), real coded genetic algorithm (RGA) and the binary coded genetic algorithm (BGA).
(e) For on-line, off-nominal system operating condition, fast acting SFL is employed for intelligent control and, thus, on-line reactive power management is carried out for the studied isolated hybrid power system model.
(f) A statistical analysis is carried out to conclude about the robustness of the comparative algorithms for this specific application.