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Optimal control strategy on battery storage systems for decoupled active-reactive power control and damping oscillations

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ABSTRACT

In recent years, battery storage systems have been widely studied in electrical networks. However, most of the studies have focused on active power in batteries. But, batteries can also produce or absorb reactive power. As well, impact of batteries on stability of the network has not been adequately addressed. Both the mentioned issues (i.e., reactive power and stability) make great impact on the battery utility such as ability of battery in energy management and power control. In order to overcome these shortcomings, current paper realizes a new control strategy on batteries for decoupled active-reactive power control. The proposed control strategy alters active power subject to constant reactive power and vice-versa. Two control loops are designed to control active and reactive powers. The control loops are equipped with PI controllers (i.e., tracking controllers). As well, both control loops of active and reactive powers are equipped with supplementary stabilizers (i.e., regulatory controllers). All controllers are simultaneously tuned by cultural-PSO-co-evolutionary (CPCE) algorithm. Several cases are simulated to demonstrate the effectiveness of the introduced strategy. It is verified that the proposed strategy is an efficient methodology to utilize battery storage systems and arising all abilities and benefits of the batteries at the same time.

1. Introduction

Battery storage systems are one the most relevant technologies in modern electric power systems and have been attracting more attention in recent years. Batteries store electrical energy in the form of electrochemical process and then the stored energy can be restored and sent back to the network [1–3]. On the topic of various techniques currently being utilized around the world, batteries can be classified into two main categories as solid state batteries and flow batteries. Solid state batteries are the electrochemical storage solutions and the main solid state batteries are electrochemical capacitors, Nickel-Cadmium batteries, Sodium-Sulfur batteries, Lithium-Ion batteries, Nickel–Metal hydride battery (NiMH), and Lead-Acid batteries [4]. On the other hand, flow batteries directly store energy in the electrolyte solution. Flow batteries have an extended cycle life. Furthermore, response time of flow batteries largely depends on the mode of operation and they mainly have no faster response time than the other batteries. Main flow batteries are Redox batteries [5], Iron-Chromium batteries, Vanadium Redox batteries, and Zinc-Bromine types [6].

Battery storage systems have been widely developed in electric power systems due to their positive features. Batteries not only can be utilized for short-term problems such as power quality, but also they can be applied as an efficient tool in long-term problems such as energy management [7]. As well, batteries are more relevant than the other storage technologies for connecting to the electrical networks. In recent years, design and implementation of bulk batteries also put an end to the problems related to low capacity of batteries [7]. Batteries are utilized in electrical networks for a variety of purposes including charging electric vehicles [8], voltage profile improvement [9], microgrid management [10], peak load shaving [11], power quality enhancement [12], frequency control [13], mitigating uncertainty related to renewable energies [14–16], relief of transmission congestion [17], profit maximization for stockholders in electricity market [18], network expansion postponing [19,20], and reliability improvement [21].

Batteries are connected to the utility grid (i.e., network) through interfacing converter. It is feasible to achieve a flexible performance between network and battery by utilizing proper control on the interfacing inverter. Several control strategies have been realized on the interfacing inverter such as dual-inverter control

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Nomenclature

Symbols and Parameters

D_m	Static friction coefficient
E_{fd}	Excitation voltage (p.u.)
E'_{fd}	Transient voltage behind x'_q (pu)
E'_q	Internal voltage behind x'_q (pu)
E_q	Voltage of q axis (p.u.)
ka	Regulation gain
K_{P1}	Proportional gain of active power controller
K_{P2}	Proportional gain of reactive power controller
K_{I1}	Integral gain of active power controller
K_{I2}	Integral gain of reactive power controller
K_{DC1}	Gain of active power stabilizer
K_{DC2}	Gain of reactive power stabilizer
M	System inertia (Mj/MVA)
P_e	Electrical power (pu)
P_m	Mechanical power (pu)
t	Time (Sec.)
T_1-T_4	Time constants of active power stabilizer (s)
T_5-T_8	Time constants of reactive power stabilizer (s)
T_a	Regulator time constant (s)
T'_{do}	Time constant of excitation circuit (s)
X_d	Steady state reactance of d axis (pu)
X'_d	Transient reactance of d axis (pu)
X_q	Steady state reactance of q axis (pu)
U_1	Output signal of active power stabilizer
U_2	Output signal of reactive power stabilizer
V_{ref}	Reference voltage (pu)
V_t	Voltage on network (pu)
$\dot{\delta}$	Differential of rotor angle (Rad/s)
ΔP	Deviations of active power
ΔQ	Deviations of reactive power
Δv	Voltage deviations
ω	Rotor speed (pu)
$\dot{\omega}$	Differential of rotor speed (pu)
ω_0	Reference rotor speed (pu)
$\Delta\omega$	Frequency deviations

scheme [22], active-reactive power and voltage-frequency control [23], voltage profile control [9], three-level neutral-point-clamped inverter control [24], frequency support [25], and decoupled active and reactive powers control [26].

As it was reviewed, batteries have been suitably investigated and studies. However, there are also several concerns that have not been dealt with effectively by the existing studies. For example, capability of batteries in producing or absorbing reactive power, or abilities for damping oscillations have not been sufficiently studied. This paper aims at dealing with such matters through providing a new control strategy focusing on active power control, reactive power control, and stability enhancement at the same time. In the proposed control strategy, active and reactive powers are controlled independent of each other based on the decupled technique. As well, stability of the network increases by utilizing proper stabilizers. The problem is mathematically expressed as a nonlinear constrained optimization problem and solved by cultural-PSO-co-evolutionary (CPCE) algorithm. Application of CPCE algorithm as an efficient Meta-heuristic optimization technique ensures the optimum results. Several large-signal and small-signal disturbances are applied on the network to demonstrate the ability of the proposed technique. Results indicate that the developed control strategy can properly control active and reactive powers independent of each other as well as damp out the oscillations.

2. Hybrid CPCE algorithm

Cultural-PSO-co-evolutionary (CPCE) algorithm is a hybrid Meta-heuristic optimization algorithm that simultaneously includes the advantages of particle swarm optimization (PSO), cultural algorithm, and Co-evolutionary algorithm [27]. This algorithm can solve all types of the optimization problems with better solution than the other algorithms [27]. As well, it has been successfully applied to solve mixed integer nonlinear problems (MINLP) in electric power systems [28].

Fig. 1 shows the main structure of CPCE algorithm. According to this figure, the population is divided into four sections as Belief spaces 1 and 2, and Population spaces 1 and 2. Suppose that N particles are used for searching in a D-dimensional space of optimization problem. First these particles are divided into two equal parts. Then each part is divided again to N11, N12, N21 and N22 particles according to equation (1). Particles of N11 and N21 are used for searching in Belief space1 (B1) and (B2) respectively. Similarly N12 and N22 particles are utilized for searching in Population space 1 (P1) and 2 (P2). Coefficients of BR1 and BR2 are introduced for the ratios between the numbers of particles in sub-spaces of B1, P1, B2 and P2. Each space contains a particle swarm. PSO operations are used for updating the particles at each space.

$$\begin{cases} N = (N_{11} + N_{12}) + (N_{21} + N_{22}) \\ N_{11} + N_{12} = N_{21} + N_{22} \\ BR_1 = \dfrac{N_{11}}{N_{12}} \\ BR_2 = \dfrac{N_{21}}{N_{22}} \end{cases} \tag{1}$$

In other words, CPCE presents a new co-evolutionary procedure between two cultural algorithms. Afterward, PSO is included into the structure of the cultural algorithm as the subspaces of Belief Spaces, and Population Spaces. Then, coordination between population's knowledge and experience is established by a set of individuals namely shared global belief space (SGBS). At each iteration of CPCE algorithm, all individuals of the sub-belief spaces are collected together into the SGBS. Next, the elite individuals of SGBS are saved and the others are substituted by reinitialized ones. As well, the affect operations in SGBS are applied for two sub-population spaces. Then, two sub-population spaces exchange their experiences in every iteration. This process is reiterated until finding the optimal solution of the problem.

More details about the methodology, formulation, and applications of CPCE algorithm can be found in [28].

3. Internal controllers and stabilizers

A typical test system including several synchronous generators and locally loads connect to the utility grid is considered as case study and show in Fig. 2. DC voltage produced by battery is converted to three-phase AC voltage by interfacing inverter. The proposed network in modeled in MATLAB software by SIMULINK toolboxes. Synchronous generators are modeled by two-axis, three-order dynamic model as given by (2). The excitation system is also modeled by a single-order transfer function as shown in (2) [29]. Lines are regarded as short transmission line and molded by a reactor. DC voltage of inverter is implemented by the DC voltage source. Three-phase two-level PWM inverter is used to model the inverter. Loads are modeled as constant impedance. The main grid is modeled by an Ac voltage source with constant voltage and frequency (i.e., infinite bus). All the equipment are chosen from