Electric Power Systems Research 149 (2017) 65–75

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Minimization of interline dynamic voltage restorers rated apparent power in an industrial area consisting of two independent feeders considering daily load variations

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ARTICLE INFO

Article history:
Received 27 September 2016
Received in revised form 17 April 2017
Accepted 18 April 2017

Keywords:
Power quality
Dynamic voltage restorer (DVR)
Interline DVR (IDVR)
Voltage sag
Load variations
Optimization
Genetic algorithm (GA)

ABSTRACT

Due to the limitation of active power exchange between dynamic voltage restorers (DVRs) in an interline DVR (IDVR), selection of the appropriate voltage for each DVR in an IDVR is very important. In previous studies, an optimization problem by selecting the “minimization of the sum of rated apparent power of DVRs” as the objective function was proposed to select the rated voltage of DVRs in an IDVR. In that problem, feeders load is assumed to be constant and equal to the rated values, while load variations in feeders affect active power exchange between the DVRs and their injected voltages. Therefore, load variations in feeders, being the main contribution of the current research, must be considered in the mentioned optimization problem. As the number of time intervals in a load curve is big, the solution space will be very large and thus, searching the entire solution space is not possible. Therefore, it is essential to use smart optimization methods For this purpose, genetic algorithm (GA) is used. By proposing a convenient strategy based on a GA for considering load variations in feeders, the sum of the rating of DVRs is minimized. In order to prove the ability of the proposed method, various examples of load variations in feeders (2, 3, and 6 time intervals) are provided. Then, using the data obtained from an actual industrial area, optimal values are determined for exiting DVRs in an IDVR structure in the case of a 24-time interval variation of feeders load.

1. Introduction

A Dynamic voltage restorer (DVR) is a series compensator installed between a utility and a load bus. Its main purpose is the protection of sensitive loads against voltage sags, swells, and voltage imbalance. This mission is accomplished by injecting a series voltage of appropriate magnitude and angle so that the load-side voltages are restored to desirable and permissible amplitude in the face of disturbed source voltage. The compensation carried out by a DVR can be performed with or without the injection of active power. DVRs with the capability to inject active power and energy have a wider compensation range. However, they need a converter or an additional energy storage device and, therefore, are more expensive [1–6]. If more than one DVR is installed in such a network, energy can be exchanged among several DVRs via a common dc bus without the need for any extra energy storage device. Therefore, in the case of a voltage disturbance in one of the feeders, the active power needed to operate the DVR located in that feeder can be received from the other healthy feeder (or feeders). This structure is called interline DVR (IDVR) and is shown in Fig. 1 for the case of two DVRs [6,7]. The capability of active power exchange between DVRs in an IDVR can significantly extend the compensating range of DVRs and eliminate the need for expensive energy storage devices.

Although many researches in this field were performed in the past [1–11], the main focus of these studies was on DVR, and fewer researches have been carried out on IDVR. In Ref. [12], an experimental case for an IDVR consisting of two DVRs has been implemented. A minimum-energy strategy for IDVR operation is proposed in Ref. [13] according to which the faulty feeder works with minimum-energy strategy and the healthy feeder acts to fix the dc-link voltage. In Ref. [14], an in-phase strategy for DVR operation is used in faulty feeder, and a virtual impedance method in healthy feeder is proposed. The performance of the IDVR in reducing voltage sags and harmonics considering its building blocks (VSI or CSI) is investigated and compared in Refs. [15,16]. In Ref. [17], the

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http://dx.doi.org/10.1016/j.epsr.2017.04.021
0378-7796/

Nomenclature

DVR	Dynamic voltage restorer
IDVR	Interline dynamic voltage restorer
VSI	Voltage-source inverter
CSI	Current-source inverter
ZSI	Z-source inverter
GA	Genetic algorithm
f-index	Faulty feeder
h-index	Healthy feeder
$S_{DVR,rated}$	DVR apparent power rating
$S_{L,rated}$	Load apparent power rating
V_{inj}	Injecting phase voltage in a DVR
P_{ex}	Power exchange between the healthy and faulty feeders
T	Time intervals of load curve
θ	DVR voltage angle
P_{DVR}	Injecting active power in a DVR
V_{Lmin}	Minimum permitted load voltage
P_{min}	Minimum DVR active power required to compensate a given voltage sag
V_S	Source voltage amplitude
δ	Source voltage angle
V_L	Load voltage amplitude
γ	Load voltage angle
S_L	Load apparent power
$\emptyset$	Load angle
I_L	Load current amplitude
β_1	Penalty factor
β_2	Penalty factor
$I_{DVR,rated}$	DVR current rating
$V_{DVR,rated}$	DVR voltage rating
VF	Source voltage amplitude for most severe voltage sag
r	A random number between 0 and 1
$I_{L,rated}$	Load current rating
$V_{L,rated}$	Load voltage rating
$P_{ex\text{-}max}$	Maximum deliverable active power from healthy feeder to faulty feeder
S_{total}	Total apparent power rating of IDVR

Z-source inverter (ZSI) is proposed in order to increase the reliability and reduce the number of switching devices in an IDVR. In Ref. [18], the displacement power factor is improved in feeders under normal conditions, by exchanging active power between feeders and an IDVR. A strategy is proposed for compensation range calculation in an IDVR encountering different voltage sag types in Ref. [19]. The compensation capability of an IDVR structure is increased in Ref. [20] by reducing feeders load power factor during a voltage sag. A design strategy based on particle swarm optimization has been used for a hysteresis voltage control of IDVR [21], and transient analysis of an IDVR is proposed using dynamic phasor representation [22]. Even though these studies gave important results, they are focused on the transient-state analysis and control methods of IDVR. This paper is concerned with steady-state operation of IDVR.

A DVR in an IDVR structure is needed to function either in compensation mode (when a voltage disturbance has occurred in its feeder) or in energy supplying mode (when a voltage disturbance has occurred in the adjacent feeder). In addition, according to load conditions of feeders (in terms of rating (kVA) and power factor) and the rated voltage of DVRs, there is a limit to the amount of active power that can be transferred from the healthy feeder to the faulty feeder [19,23]. Therefore, a suitable design strategy of an IDVR should assure compensating different types of voltage disturbances of each of the feeders, and to achieve the minimum DVR voltage ratings. The optimal design strategy presented in Ref. [23] is adopted only by considering the rated conditions for loads of both feeders and load curves have not been considered, while, according to Refs. [19,23], the active power transmitted from the DVR of the healthy feeder to the faulty feeder depends on the rating and power factor of the load of the feeders. Thus, load variations in feeders can influence the exchanged active power and injected voltage of DVRs in both feeders. Therefore, if the optimal design problem of an IDVR only considers the rated load conditions, then full compensation of voltage sags under load variations may be impossible for the designed IDVR, or the selected voltage ratings of DVRs in the designed IDVR may be unreasonably large. Consequently, feeder load variations must be considered in the optimum design of DVR, which is the main purpose of the current research.

Another important point to note is that if the number of the time intervals of the load curve in feeders is large (in practice, it is), the number of variables increases. Therefore, the solution space of the optimization problem will be very large and, practically, it is not possible to search inside the entire solution space. Hence, it is essential to use intelligent methods for solving the optimization problem. Among the intelligent optimization methods, the genetic algorithm (GA) is an efficient algorithm and its ability to solve different optimization problems has been proven [24–26]. Therefore, in this paper, the GA is used to solve the optimization problem. In order to prove the ability of the proposed method, the optimization problem is solved considering 2, 3, and 6 time intervals of load variations in feeders. The results are compared with the method proposed in Ref. [23]. Then, an actual industrial area is chosen, and by using the data obtained from it, optimal values are determined for existing DVRs in an IDVR in a range of 24 time intervals of load variations in feeders.

Consequently, some important innovative contributions of this work can be listed as follows:

1. Minimizing IDVR rating considering load variations in feeders,
2. Applying the GA method for solving the proposed optimization problem,
3. Generalizing the optimization problem presented in [23] by considering the load variations in feeders, and
4. Solving the proposed optimization problem for an actual industrial area by taking full variations (24 time intervals) in a daily load curve.

The rest of paper is organized as follows: Section 2 presents steady state modeling and formulation of an IDVR. Section 3 focuses on the problem of IDVR rating optimal design considering load variations in feeders. The proposed design strategy is presented in Section 4. Results based on the proposed design procedure are illustrated and discussed in Section 5. Finally, Section 6 gives some conclusions of the current research.

2. Formulation of IDVR steady state operation

The steady state modeling and description of the relations in an IDVR are presented in this section.

2.1. IDVR equivalent circuit

Fig. 2 illustrates the steady-state equivalent circuit of an IDVR consisting of two DVRs. The analysis in this section can be also extended to an IDVR structure with more than two DVRs. In Fig. 2, subscripts “f” and “h” represent “faulty” and “healthy” feeder parameters respectively. It is also assumed that, at any moment, only one feeder (the faulty one) is experiencing voltage sag, and