Electrical Power and Energy Systems 54 (2014) 658–663

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Short Communication

New technique for enhancing the accuracy of HVDC systems in state estimation

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ARTICLE INFO

Article history:
Received 11 March 2013
Received in revised form 29 July 2013
Accepted 23 August 2013

Keywords:
Energy management systems
HVDC system
Topology processing
State estimation

ABSTRACT

This paper describes a new technique for enhancing the accuracy of high-voltage direct current (HVDC) systems in the state estimation of the Korean energy management systems. New methodology, which includes the accurate modeling of the HVDC systems using switching devices, the determination of the operating mode of the HVDC systems, and a fast-decoupled weighted least square approach with a modified gain matrix, is proposed to enhance the accuracy of state estimation. Especially, the DC current is defined as a state variable to estimate the HVDC systems. These algorithms are verified in on-line environment. The test results show that the proposed algorithm operates correctly for various situations.
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1. Introduction

Because of deregulation and constant expansion in many countries and the increasing trend of interconnection of power grids, the role of energy management systems (EMSs) has changed significantly [1]. The purpose of an EMS is to monitor, analyze, and control power systems with four major platforms: supervisory control and data acquisition systems, database, user interfaces, and applications. Recently, the Korean electric power system has experienced rolling blackouts. Unusually high temperature and maintenance of some power plants led to rolling blackouts. One of the most challenging tasks for today's power system engineers in Korea is to develop the Korean EMS (K-EMS) for use by operators for the operation and planning of the power system. The use of K-EMS will provide a convenient operation environment that considers the dynamic and geographical characteristics of the power system. Since its completion in 1998, the ±180 kV 300 MW HVDC #1 in the Korean electric power system conveys relatively cheap electric power from the Haenam S/S on the mainland to the Jeju island by means of an undersea 101 km DC cable. In addition, the ±250 kV 400 MW HVDC #2 from Jindo S/S on the mainland to the Jeju island by means of an undersea 122 km DC cable is currently under construction.

Many have researched this topic and proposed various techniques [2–4]. In order to satisfy the critical performance requirements for network security, these research efforts were directed at the development of network analysis applications. Topics related to state estimation techniques such as HVDC and flexible alternating current transmission system (FACTS) have been reviewed due to the advanced technology of power electronics. The HVDC model has already been devised and implemented by most of the commercial EMS vendors. The methodology and concept of their algorithms are well established concepts. However, it can be difficult for this approach to estimate the actual state of the HVDC systems. Therefore, a robust topology processing and state estimation, which is able to calculate the state of specific models such as HVDC and FACTS, should be applied to the large-scale power systems.

In this paper, new methodology for enhancing the accuracy of the HVDC systems in state estimation is described. We first introduce the proposed structure of the HVDC systems for topology processing. Then, topology processing and state estimation based on the novel methodology for analyzing the large-scale power systems including HVDC systems is presented. Finally, we have verified and tested the proposed algorithm using on-line field test environments for the Korean electric power system. To demonstrate the validity of the proposed algorithm, comparative simulations between the K-EMS and existing EMS for the power system were conducted.

2. The proposed methodology for HVDC system

The design of the network analysis applications for fast and reliable decision making might be considered for the accurate modeling of power system components.

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http://dx.doi.org/10.1016/j.ijepes.2013.08.022

2.1. The proposed HVDC modeling

In the Korean power system, the HVDC model of operating EMS installed by the major EMS vendor was different from actual HVDC system. Although the converter transformer connected to the actual HVDC system is three-winding transformer, the model of the operating EMS is two-winding transformer. Also, the HVDC system of the operating EMS is modeled as a virtual injection component. The gap between two systems has more effect on the result of state estimation and power flow when the emergency situation occurred.

As shown in Fig. 1(a), the proposed HVDC system represents a static table and a dynamic table for a system hierarchic layer using nodes, switches, DC poles, DC converters, DC lines, and three-winding transformers. Where node and switch include both AC and DC systems. These components have relationships using one or more of the three link types such as head index, sibling index and indirect index. The head index is a pointer to the first record on linked list of records in another table and the sibling index is a pointer to the next record that is related to the head index. The indirect index is a pointer to the 1:1 link. For example, we can analyze the relationship between DC poles and DC converters, using the head index from the DC pole to the DC converter and sibling index of that DC pole in the DC converter table. In addition, the relationship between nodes and DC converters is the 1:1 link. In order to create and maintain the HVDC system in the K-EMS, the offline database modeler is developed based on the common information model (CIM) and is stored in an Oracle relation database.

In the K-EMS, the DC current and DC power at one or both terminals of the DC lines are measured, while the status of DC switches was not measured. The use of the DC nodes and the DC switches for the accurate analysis of the HVDC system can provides a very strong benefit in handing various operating modes of HVDC system, modeling different HVDC system such as point to point and back to back, and understanding of the basic concepts of HVDC modeling and operation. Also, the extensive study from the viewpoint of HVDC system, the status of DC switches should be automatically determined by the values of the measured DC current and DC power.

2.2. The proposed HVDC topology processing

The primary objective of the proposed topology processing algorithm in this paper is to identify the operating modes of the HVDC system, such as normal, bypass, and blocking. In addition, the in- or out-of-service of the converters and DC lines are derived by this processing. As mentioned before, the HVDC model using switching devices is proposed in Fig. 1(a) [5]. It has the advantage that the operating modes of the HVDC system could be changed by handling the status of switching devices. As shown in Fig. 1(b), if DCCB #2, #5, #6, #11, #14, and #15 are open, the operating mode is bypass. In addition, if DCCB #2, #6, #8, #9, #11, #15, #17, and #18 are open, the operating mode is monopole. In Fig. 1(b), the demarcation points between the AC system and the DC system are the primary winding terminal buses of transformer. The converter transformers are excluded from the AC system and included in the DC system. Therefore, the flows in the transformers' primary windings are calculated from the DC system and used as injection into the AC system. The procedure to analyze the HVDC system is described as follows:

- *Step 1*: Create mapping table between the nodes of all the stations in the AC system and buses.
- *Step 2*: Identify the state of all the buses and equipment in each electrical island.
- *Step 3*: Establish buses at each end of DC line to include all the nodes connected with closed switches.
- *Step 4*: Check whether the other DC line is connected in parallel. If this is the case, mark the other DC line as processed.
- *Step 5*: Find the converters that are connected to the DC line terminals. If one or both buses do not include converter nodes, mark the DC line as out of service.
- *Step 6*: Identify the associated converter transformers using the converters' AC nodes. Check the state of the converter transformers.
- *Step 7*: Go back to the step 3 until all the DC lines are processed.

2.3. The proposed HVDC state estimation

The conventional method for the HVDC systems was finally estimated using virtual injection components in the state estimation, excluding the completion of the HVDC model. The buses installed in the HVDC systems were virtually equipped with generator and load models, with which these buses were injected for active and reactive powers. Fig. 2(a) shows the conventional method of state estimation for the HVDC systems. Although the conventional method has good convergence characteristics, the estimated value for the HVDC systems can be included in poor results.

The weighted least square (WLS) state estimation can be mathematically formulated as the following optimization problem [2–4]:

$$\min J(x) = \sum_{i=1}^{m}[z - h(x)]^T R^{-1}[z - h(x)] \tag{1}$$

where x, z, and h represent the vector relating the estimated state variables, the measurement vector, and the vector of the nonlinear function associated with the measurement of the state variables, respectively. R is the diagonal element of the covariance matrix of the measurement error. The solution of this nonlinear problem was calculated iteratively by solving the following equation:

$$H(x)^T R^{-1} H(x) \cdot \Delta x = H(x) R^{-1} \cdot \Delta z \tag{2}$$

In left-hand side of Eq. (2), $H(x)^T R^{-1} H(x)$ denotes the gain matrix. Fast-decoupled WLS method calculates two fixed gain matrices for the voltage angle and the voltage magnitude. This paper suggests modified gain matrix that deals with the additional DC measurements and the DC current state variable. The right-hand side of Eq. (2) will be calculated in each iteration. $\Delta Z = Z - H(x)$ is the measurement residue. To estimate the accurate state of the HVDC system, a new approach for the MW and Mvar iterations based on fast-decoupled WLS method is proposed in this paper.

For MW iteration, the DC current is defined as a state variable. The following DC model measurements will be included in the state estimation process and will be expressed as functions of the DC current. The measurements are the DC current, the DC power at one or both terminals of the DC line, the MW flow on the primary windings of the converter transformers, and the injections at the demarcation buses. These measurements will be used to calculate the initial value for the DC current. When the gain matrix for the MW calculation is created, the entries related to the DC current are added as shown in Fig. 2(b).

For Mvar iteration, no state variables related to the DC network are defined in the Mvar iteration. The DC voltage at one end of the DC line must be specified and used as a reference. The available DC voltages are the telemetered DC voltage and the constant control voltage value at Haenam. With the DC voltage known, the DC current calculated in the MW iteration and the voltage at the demarcation buses calculated in the MVAr iteration, the firing

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