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Appropriate selection of shunt compensation reactor in parallel transmission lines: A case study

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ABSTRACT

Shunt reactors are widely deployed as effective compensation means against the capacitive behavior of high voltage transmission lines. Subsequent to load rejection or light load conditions, a resonance phenomenon is highly potent due to remarkable capacitive feature of these lines. Reactor failure, threatening the interior insulation of high voltage equipment connected to the line, and early aging of insulations are some of the main concerns regarding resonance voltages. To study the phenomenon, different cases including complete disconnection of the transmission line, single and double pole operation of breakers, and short circuit faults on the de-energized line are simulated with two different knee points of reactor saturation. A sensitivity analysis is also conducted considering the soil resistivity and corona phenomenon. Different solutions such as neutral reactors and resistors, complete transposition of the circuits, capacitor bank and replacing the ground disconnector switches with breakers are examined in the worst case to limit the resonance overvoltage. In contrast to previous contributions, it is shown that when the shunt compensation reactor is not appropriately determined, none of the solution methods alone can resolve the resonance phenomenon. Hence, an exact and carefully-selected compensation level is of great significance.

1. Introduction

In high voltage power system installations, inaccurate modeling of overvoltages in the design and selection process can contribute to the equipment failure and service interruptions. This, in turn, not only disturbs the electrification process and reduces the reliability metrics but also increases the equipment maintenance and replacement costs [1]. A precise understanding of overvoltages mechanisms yields beneficial knowledge to contemplate effective precautions against the formation of these phenomena and to prevent the equipment major failures. Besides, a highly reliable electrification system is achieved [2].

Among different overvoltages, the resonance and ferroresonance phenomena are treated with a great importance in power system studies. Three main issues weight up such an importance. The first reason deals with permanent nature of these overvoltages. Typically, they last for a long time on power system apparatuses rendering an increased insulation stress which intensifies the chance of equipment failure [3]. The second point refers to the magnitude of these overvoltages recorded to be much larger than the nominal operating voltages. Normally, the equipment insulation cannot withstand such critical overvoltages for a long time [4]. The third issue speaks for unusual and hardly-predictable conditions which may stimulate resonance and ferroresonance phenomena with a high occurrence probability [5]. To establish a good knowledge of different occurrence conditions and avert the significant technical and economical losses, exact and thorough investigation of resonance overvoltages seems essential [6].

One of the common cases which raise the probability of the resonance phenomenon in the grid is a double-circuit line compensated with a shunt reactor. Shunt reactors are usually used on high voltage transmission lines to limit overvoltages during the line energization, load rejection, and under light load conditions. However, upon the disconnection of one phase or line, the resonance can occur since the shunt reactors are fed through capacitive coupling from the adjacent phases or lines. If the resonance phenomenon is ignited, significant voltage drop is recorded over the whole line which not only threatens the equipment insulation but also saturates the magnetic core of the reactor [7,8]. The core saturation comes with a decrement in reactor impedance and affects its operation conditions and characteristics. Moreover, the magnetic current of the reactor increases significantly accompanied with an enhancement in the flux density. Accordingly, the

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core temperature increases and burns the isolation layers in core lamination which contributes to mechanical vibrations. Different cases have been reported in the literature regarding this phenomenon. As an instance, authors in [9] report a parallel resonant circuit where only one circuit is energized in a double-circuit line.

The next consequence of the resonance phenomenon is recovery voltages with a high slope and magnitude during reclosing time of circuit breakers (CBs). The single phase auto-reclosing is an effective method to clear and restore single line to ground faults. However, it can bring a shunt compensated line into resonance conditions intensifying the difficulties ahead of the CBs operation [10]. This situation results in a series resonant circuit detailed in [11,12]. Unbalanced open phase conditions can also lead to a similar case where one or two poles of CBs get stuck during a switching operation. In high voltage lines, CBs generally comprise independent phases and, therefore, it is probable to have one of the phases act with some delay or encounter a failure [9,13].

The aforementioned explanations show that proper precautions are required to prevent or mitigate the resonance occurrence. Different methods have been suggested to decrease the resonance voltages over reactor terminals. A suitable neutral reactor or a high voltage resistor connected between the shunt reactor neutral and the ground can decrease the induced resonance overvoltages, and also limit the secondary arc current on shunt compensated lines [14]. Complete transposition of the circuits, adding new reactors, using a capacitor bank, replacing the ground disconnector switches with breakers, and ungrounding the neutral of the reactor are other solutions proposed to limit the resonance overvoltage [9,15,16].

In this paper, in order to have a practical analysis, a real test system in south part of Iran, i.e. Minab-Jask double-circuit 230 kV un-transposed transmission line which is compensated with two 25 MVAr reactors at the Jask substation is investigated. This line has also the experience of resonance phenomena. It is important to study different cases to estimate the induced voltages and to propose appropriate solutions for alleviating the phenomenon. Therefore, extensive simulation studies including complete disconnection of the transmission line, single and double pole operation of CBs, and a short circuit fault on the de-energized line are explored with a particular focus on the worst case. In further steps, the effects of soil resistivity and corona are investigated on resonance voltages. Different methods could be perceived as effective countermeasures against resonance voltages which are carefully probed through the manuscript. Based on the conducted analysis, a safe range of shunt compensation reactor is determined for the transmission line with the least chance of resonance phenomena. The conducted study and the solutions proposed here can assist in preventing the resonance overvoltages in the design and installation stages of transmission lines in similar cases.

2. Test system specifications

Fig. 1 depicts the single-line diagram of the investigated circuit. As can be seen, the double-circuit transmission lines are expanded between the Minab and Zarabad substations. However, only the portions which connecting the Minab and Jask substations are equipped with shunt reactors. One reactor is installed in Jakdan-Jask transmission line and the other one in Senderk-Jask transmission line. It should be noted that both of the reactors are installed at the ending point of Jask substation. These reactors have the nominal capacities of 25 MVAr in rated voltage of 245 kV. As well, they are featured with positive and zero sequence impedances equal to 2337 Ω/phase and 1361 Ω/phase. Jask-Zarabad double-circuit transmission line is operated in an unusual manner in which one of the lines is fed through a 230 kV voltage level from Jask and the other one is connected to an independent 63 kV system which is not shown in Fig. 1. Moreover, as can be seen in the figure, the upper outgoing bay of the substation is connected to the bottom line which in normal situation should be connected to the bottom substation outgoing bay. This double-circuit transmission line does not include any shunt compensation reactor and hence is modeled as a normal transmission line. As there is no any risk of resonance phenomena in this line, it is not included in detailed analyses. Table 1 gathers the line parameters and the conductor types in the investigated system.

Table 1
Transmission lines parameters and conductor types.

Line No.	Parameters				
	Conductor type	Conductor diameter (mm)	Resistance (Ω/km)	Voltage level (kV)	Line length (km)
836	SQUAB	24.51	0.0633	230	85
837	SQUAB	24.51	0.0633	230	42
839	SQUAB	24.51	0.0633	230	151
814	SQUAB	24.51	0.0633	230	108
818	CANARY	29.52	0.0944	230	170

Transmission tower of the Minab-Jask line is of T/L 230 kV type with tower model IS2-3. The phase arrangement and the distance between the phases are shown in Fig. 2. Here, only the height of the main mast is considered and the additional parts are not regarded.

The Minab-Jask transmission line is modeled as a distributed line in PSCAD/EMTDC platform. However, the Jask-Zarabad line is not included in detailed studies and is represented based on lumped models since there is no reactor in this line.

The PSCAD lacks a suitable reactor model with saturation capability. Therefore, for representing a non-linear reactor, a saturable unit transformer with an inductor in its secondary circuit is deployed. Fig. 3 illustrates one phase of such a configuration. In the model utilized, three units of Fig. 3 are connected in a star topology to represent a three phase shunt reactor. In normal conditions, the reactor characteristics are duplicated by the inductor. In this way, the transformer parameters are assigned such that a linear inductor is seen from its primary circuit. Saturation feature of the inductor is mimicked through the saturable unit transformer. Above the corresponding voltage level of inductor knee points, the transformer is saturated and reveals the anticipated features of the reactor saturation conditions. The saturation curve of the reactor with two different knee points 1.25 and 1.5 p.u. and a slope ratio of 30% is considered in the simulation studies.

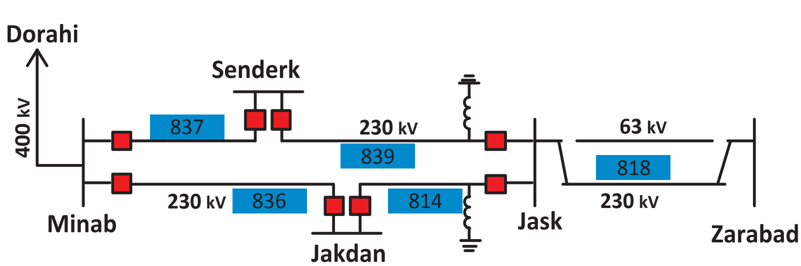

Fig. 1. Single-line diagram of the investigated power system.