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## Optimal Planning of Transmission Line Charging Mode During Black Start of a Hydroelectric Unit

### ARTICLE INFO

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### ABSTRACT

After the occurrence of blackouts, the most important subject is that how fast the electric service is restored. Power system restoration is an immensely complex issue and there should be a plan to be executed within the shortest time period. This plan has three main stages of black start, network reconfiguration and load restoration. In the black start stage, operators and experts may face with several problems; for instance, the unsuccessful connection of the long high voltage transmission line connected to the electrical source. In this situation, the generator may be tripped because of the unsuitable setting of its line charging mode or high absorbed reactive power. In order to solve this problem, the line charging process is defined as a nonlinear programming problem, and it is optimized by using MATLAB software in this paper. Therefore, the line charging mode of a hydro power plant is defined as an optimization problem. A nonlinear programming problem with considering the effect of transmission line parameters and installed shunt reactors in sending and receiving end buses is formulated. An iterative procedure is applied for solving the proposed problem. The optimized process is performed on a small part of a large grid which includes a 250 MW hydroelectric unit and a 400 KV transmission system. Simulations and field test results show the effectiveness of the optimal planning.

**Keywords:** Power System restoration; Black start; Line charging mode; nonlinear programming.

## 1 Introduction

As you know recent blackouts in all around the world show that the power system is so vulnerable to the unpredictable cascading outages at the stressed conditions and it is so difficult to predict and to prevent this event [1]. Therefore, a power system restoration plan should be considered to restore the entire power network very quickly. A power system restoration plan consists of three phases: preparation, network reconfiguration and load restoration [2]. In the first phase, the pre-considered generating units that can be started automatically, called black start units (BSUs) are turned on [3]. Then, the transmission paths are established to crank the Non-black start units (NBSUs). There are some problems in cranking process when the transmission lines are energized and connected to BSU. One of these problems is the existence of the high capacitance charge of transmission line and the exceeding reactive power that should be absorbed by BSU [4]. This reactive power may damage the rotor core of BSU and this, in turn, it will be tripped. A suitable setting of the excitation system of BSU and utilization of reactive power balancing device such as shunt reactor or Thyristor Controlled Reactor (TCR) can desirably decrease this reactive power [5]. Some methods such as using the sufficient under-excitation capacity of generators, connecting the shunt reactors, disconnecting shunt capacitors, and regulating the transformer tap were presented to overcome the sustained over-voltage [6-9]. A simple way was addressed in [10] for evaluating the sending and receiving end bus over-voltages. Reference [11] presented a sensitivity analysis method to search the most efficient changes to be applied to network for decreasing of the voltage level.

Reactive power control issue during the black start process is addressed in [12-13]. In [12], a multivariable control solution for improving the voltage stability during black start-up is given. The control design in [12] is performed by using a linearized gain for the centralized multiunit control. In [13], a nonlinear programming module with the expert system is planned to consider the differences between the restoration and the normal situation of power system in order to control the over voltage problem. In reference [14], the voltage control is locally done in Swedish grid by using the shunt device and synchronized generator.

Despite the above efforts to solve the problem of the voltage control, the effect of transmission line parameters and the installed shunt reactors in sending and receiving end buses are not coordinately considered. In this paper, the line charging process is defined as a nonlinear programming problem with considering the effect of transmission line parameters and installed shunt reactors in sending and receiving end buses, and it is optimized by using MATLAB software. The optimal planning is performed on a grid which includes a 250 MW hydroelectric unit and a 400 KV transmission system.

In general, the main contributions of paper are addressed as follow:

- The line charging mode of a hydro power plant is defined as an optimization problem.
- A nonlinear programming problem with considering the effect of transmission line parameters and installed shunt reactors in sending and receiving end buses is formulated.
- An iterative procedure is applied for solving the proposed problem.

The organization of this paper is as follows:

- Section 2 is dedicated to the problem formulation with its objective function and related constraints.
- Section 3 presents the simulation results obtained through the implementation of proposed method.
- Section 4 concludes the paper by summarizing the key findings and their implications.

## 2 Problem Formulation

### 2.1 Lossless Distributed Parameter Lines

A distributed model of transmission line is considered in this paper. This model is characterized by two parameters as shown in Figure 1 [15]; series impedance and shunt admittance. The series impedance includes resistance ( $r$ ) and inductance ( $l$ ). The shunt part consists of a conductance ( $g$ ) and a capacitance ( $c$ ).

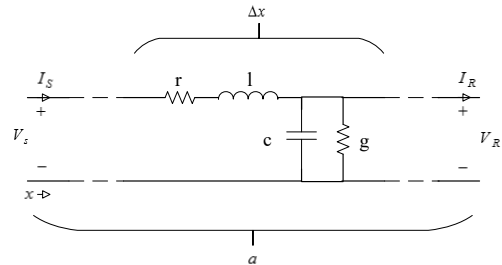


Figure 1: Distributed parameter model-based transmission line [15]

The propagated electrical energy through the line is given by the following fundamental equations [15],

$$\begin{cases} \frac{\partial^2 V}{\partial x^2} = zyV \\ \frac{\partial^2 I}{\partial x^2} = zyI \end{cases} \quad (1)$$

Where the parameter  $ZY$  includes the resistance ( $r$ ), inductance ( $l$ ), conductance ( $g$ ) and capacitance ( $c$ ) of transmission line, is defined as  $(r + j\omega l)(g + j\omega c)$ .

If the transmission line is considered as a lossless line, the general solutions of Eq. (1) will be obtained as [15]

$$\begin{cases} V(x) = V_R \cos \beta (a - x) - jZ_0 I_R \sin \beta (a - x) \\ I(x) = I_R \cos \beta (a - x) - j \frac{V_R}{Z_0} \sin \beta (a - x) \end{cases} \quad (2)$$

Where  $V(x)$  and  $I(x)$  are the voltage and current of any point at a distance  $x$  from the receiving end bus. In Eq. (2),  $Z_0 = \sqrt{\frac{l}{c}}$ ,  $\beta = \omega\sqrt{l \cdot c}$ ,  $a$ ,  $V_R$  and  $I_R$  refer to the surge impedance, imaginary part of propagation constant, the length of transmission line, the voltage and current of receiving end bus respectively.

The sending end bus voltage ( $V_S$ ) can be calculated as follows [15];

$$\begin{cases} V(x=0) = V_S = V_R \cos \beta a \\ V_R = \frac{V_S}{\cos \beta a} = \frac{V_S}{\cos \theta} \end{cases} \quad (3)$$

Where  $\beta a = \theta$  is defined as the electrical length of transmission line. At this condition, it is assumed that the load current ( $I_R$ ) is zero. The reactive power that can be absorbed ( $Q_s$ ) by the generator during the line charging can be calculated by Eqn. (4) [15].

$$Q_S = \text{Im}\{V_S \cdot I_S^*\} \quad (4)$$

By substituting Eq. (1) in Eq. (4) at sending end bus ( $x=0$ ), Eq. (4) can be rewritten as [15]

$$\begin{cases} Q_S = \frac{V_R^2}{Z_0} \cos \theta \cdot \sin \theta \\ = \frac{V_S^2}{Z_0} \tan \theta \end{cases} \quad (5)$$

## 2.2 Compensated Lossless Distributed Parameter Lines

The lossless distributed parameter line can be compensated by installing the shunt reactor at the receiving end to reduce the over voltage at the end of line and also the absorbed reactive power by generator. Figure 2 shows the compensated lossless distributed parameter line.

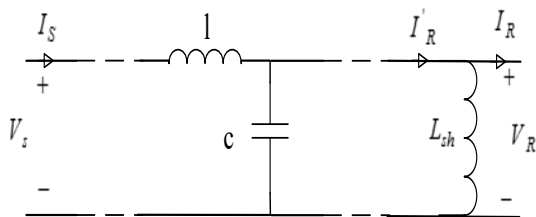


Figure 2: The model of compensated lossless transmission line

By installing shunt reactor ( $L_{sh}$ ), the receiving end voltage and the absorbed reactive power of generator can be given as follows [15]:

$$V_R = \frac{V_S}{\cos \theta'} = \frac{V_S}{\cos(\theta\sqrt{1-K_{sh}})} \quad (6)$$

$$\begin{cases} Q_S = \frac{V_S^2}{Z_0'} \tan \theta' \\ \theta' = \theta\sqrt{1-K_{sh}} \\ Z_0' = \frac{Z_0}{\sqrt{1-K_{sh}}} \end{cases} \quad (7)$$

Where  $K_{sh}$  is the degree of compensation of installed shunt reactor at the receiving end.

## 2.3 Objective Function

The main target after energizing transmission line (during black start process) is to reduce the over voltage to energize the receiving end bus and to restore the relevant load. Therefore, the objective function to be minimized, as given in Eq. (8), is defined as the difference between the receiving end voltage and its reference value.

$$OF = \min |V_R - V_{Rref}| \quad (8)$$

By considering Eq. (6) and Eq. (8), the objective function can be rewritten as

$$OF = \min \left| \frac{V_S}{\cos(\theta\sqrt{1-K_{sh}})} - V_{Rref} \right| \quad (9)$$

Subject to:

$$|Q_S| \leq |Q_{Smax}| \quad (10)$$

Where  $Q_{Smax}$  refers to the maximum permissible limitation of absorbed reactive power. Applying Eq. (7) in Eq. (10), the constraint can be formulated as

$$\frac{V_S^2}{Z_0'} \tan(\theta\sqrt{1-K_{sh}}) \leq Q_{Smax} \quad (11)$$

Finally, the optimization problem for solving the line charging process during the black start stage is defined as a non-linear programming problem and is formulated as

$$\begin{cases} OF = \min \left| \frac{V_S}{\cos(\theta\sqrt{1-K_{sh}})} - V_{Rref} \right| \\ s. t \\ V_S^2 \cdot \sqrt{1-K_{sh}} \cdot \tan(\theta\sqrt{1-K_{sh}}) \leq Q_{Smax} \\ V_S \geq 0, \quad K_{sh} \geq 0 \end{cases} \quad (12)$$

In Eq. (12),  $K_{sh}$ ,  $V_S$  are decision variables. Then, Eq. (12) is optimized by the suitable setting of both the generator voltage and compensating degree of shunt reactor at the receiving end of transmission line. Generally, the flowchart of the proposed method is shown in Figure 3. The MATLAB software is used to solve the optimization problem.

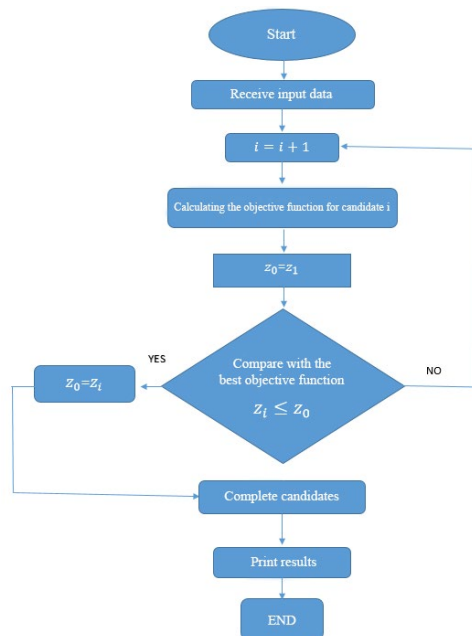


Figure 3: Flowchart of the proposed method

### 3 Simulation and Test Results

In this section, the optimization process is implemented for both simulations and real case study. This section includes two parts. In the first part, the results of the simulations are discussed. In the second part, the results of the real case and the relevant discussion are given.

#### 3.1 Simulation

The single line diagram of 3-bus power system, as shown in Figure 4, is selected for the simulation. The information of this system which is the same as the real case (field test) is given in Table 1. The base MVA is also 100 MVA.

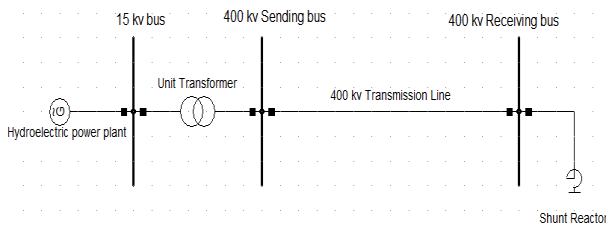


Figure 4: Single line diagram of 3-bus power system

Table 1: The information of Study System

The optimal values of  $K_{sh}$  and  $V_s$  are calculated by using MATLAB software and are shown in Table 2.

Table 2: Results of Optimization

Variable	$V_s$	$K_{sh}$	Objective function
Value (p.u)	0.962	0.38	$4.9 \times 10^{-9}$

The simulation results for two cases of before and after optimization are given in Table 3. The first row implies that the receiving-end bus voltage and the absorbed reactive power of generator are accurately tuned.

Table 3: Comparison of Results considering optimization process

Condition	Absorbed reactive power (MVAR)	Voltage of terminal of generator (KV)	Voltage of receiving bus (KV)
With optimized $V_s$ & $K_{sh}$	-105.8	17.32	400
With optimized $V_s$	-174.3	17.32	409.64
With optimized $K_{sh}$	-114.9	18	415.6
Without optimization	-188.3	18	425.8

Table III also shows that the uncoordinated setting of both  $V_s$  and  $K_{sh}$  causes either the absorbed reactive power or the receiving-end bus voltage to be increased. For example, the second row of Table III shows that by only tuning  $V_s$  the voltage of the receiving-end bus is improved, while the absorbed reactive power increases undesirably. This situation can trip the generator and delay the restoration process.

Therefore, the coordinated tuning of both  $V_s$  and  $K_{sh}$  is a suitable choice during the line charging mode.

#### 3.2 Field Test Results

The proposed method is now applied to a real case, which is a small part of a large power network. The line charging process of generator starts after coordinately setting of both  $V_s$  and  $K_{sh}$  according to Table 2. This test is initialized at 02:18 AM. Figure 4 shows the results during the line charging mode of the system. This figure is extracted from monitoring device of supervisory control and data acquisition (SCADA) system in control center.

Fig. 4 shows the step by step increase of the sending end bus voltage. This voltage started from zero and continued till 380 KV and remained in this value. During this process the transmission line is energized when the voltage is 100 KV. Then, the absorbed reactive power by generator increased. Another line in Figure 4 shows the reactive power that is absorbed by generator after energizing the transmission line. According to this figure, the absorbed reactive power increased due to the increment of the generator voltage and stopped when the absorbed reactive power reached to its maximum limitation. At this point, the absorbed reactive power is recorded as 106 MVAR as shown in Figure 5. The

Generator	Rated active power (MW)	Rated reactive power (MVAR)	Rated voltage (KV)
	[0 250]	[-110 150]	18
Transformer	Rated power (MVA)	Ratio	$U_k$ %
	288	18/400	11.5
Transmission Line	Length (km)	L (mH/km)	C (uF/km)
	204	0.954	0.012
Shunt Reactor	Rated reactive power (MVAR)	Rated voltage (KV)	Number of steps
	0-50	400	2

main target in this paper is to minimize the receiving end bus voltage. Figure 6 presents the deviation of this voltage. The value of the assigned point in this curve (399 KV at 02:33 AM) implies that the objective function value given by Eqn. (12) is 0.0025 in per unit. Therefore, the load connected to the receiving end bus can be restored.

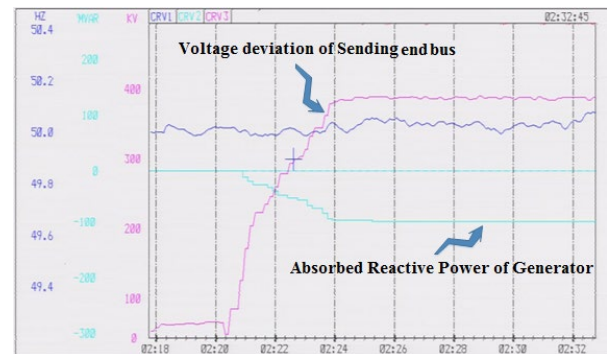


Figure 5: Voltage deviation of sending end bus and absorbed reactive power of generator during line charging process

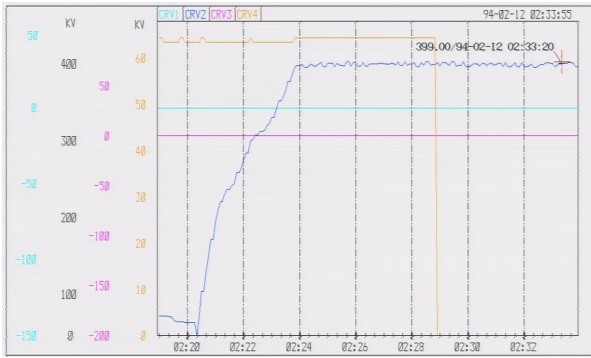


Figure 6: Voltage deviation of receiving end bus during line charging process

## 4 Conclusion

In this paper, one of the problems of black start stage, the line charging process, is defined as a nonlinear programming problem with considering the effect of transmission line parameters and installed shunt reactors in sending and receiving end, and then solved by using MATLAB software. The proposed approach is implemented on both simulations and actual case that have similar characteristics. The results show the effectiveness of the proposed method.

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