Guidelines for Selection of Neutral Reactors rating for Shunt Compensated EHV Transmission Lines

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Abstract— Neutral reactors are generally employed in shunt compensated long EHV transmission line to limit resonance overvoltages induced on de-energized conductors due to parallel energized circuits and stuck breaker conditions, and to reduce the secondary arc current during single phase auto-reclosing. The objective of this paper is to provide the guidelines for selection of properly rated neutral reactors for shunt compensated EHV transmission lines by conducting system studies. These guidelines are demonstrated through a 360 km, 400 kV double circuit line with 80 MVar shunt reactor at both ends of each circuit. Studies were conducted using MiPower power system analyses package.

Keywords—induced voltage; neutral reactor; recovery voltage; secondary arc current; single pole switching; stuck breaker.

I. INTRODUCTION

SHUNT reactors are generally provided on long EHV transmission lines to limit overvoltages during line energization, load rejection and light load conditions. These reactors are typically rated to compensate about 20 to 70% of the line shunt capacitance. Although they limit overvoltages under the above conditions, the shunt reactors could actually increase voltages induced onto de-energized line conductors, due to resonance from the energized conductors of same circuit or another circuit on the same right of way. These overvoltages could be limited by means of a reactor, termed a neutral grounding reactor (NGR), connected between the shunt reactor neutral and ground. The majority of transmission line faults are temporary short circuits. Automatic single phase reclosing is used to clear single-phase-to-ground faults, which are about 80% of the transient faults. The short circuit arc is usually self-extinguishing after opening the transmission line circuit breakers. High-speed re-closure of transmission line circuit breakers can improve system stability. As the voltage level increases arc de-ionization time increases as well, endangering system stability. Application of automatic single phase reclosing makes it possible to increase system stability even for extremely high voltage transmission lines. To enable successful fast reclosing, NGR is normally used when transmission line is compensated with shunt reactors [3].

During the dead time of Single Pole Switching (SPS), extinction of the main transient arc current should take place. However, the faulted phase remains capacitively and inductively coupled with the energized un-faulted phases resulting in continuation of the fault current, which are known as secondary arc currents. In case of SPS on double circuit EHV line, the secondary arc is maintained not only by the inter-phase capacitive coupling between faulted phases and energized phases of the same circuit, but also by the mutual coupling of the other healthy circuit.

The magnitude of the secondary arc current and the recovery voltage are the most important factors, which determine whether or not the secondary arc will be self-extinguishing. Use of properly rated NGR at the neutral point of the shunt reactor ensures secondary arc extinction and successful SPS [3].

The parameters of NGR are initially determined based on steady state analyses, considering equivalent networks on either side of the transmission line under consideration. Appropriate rating of the NGR is then selected by performing transient analysis studies considering arc modeling, arc extinction time and single line to ground fault at different points on the transmission line. Both steady state and transient analyses studies have to be performed using EMTP-type program.

II. SELECTION OF NGR RATING

A. Equivalent network model for simulations

Equivalent network model is derived based on load flow and short circuit study results and a two bus equivalent system is formed as shown in Figures 1 and 2 (single circuit or double circuit configuration).

![Figure 1. Equivalent network model for a typical single circuit](image1)

![Figure 2. Equivalent network model for a typical double circuit](image2)
Equivalent sources at sending and receiving end are represented using positive and zero sequence impedance values corresponding to the expected fault levels at both ends. The single/double circuit transmission line is modeled by 3x3/6x6 phase impedance matrix (self and mutual impedances) and a 3x3/6x6 phase admittance matrix (self and mutual capacitance). The investigation of NGR application is performed for actual transposition (typical transposition of single circuit and double circuit are shown in Figures 1 and 2 respectively). Transmission line shunt reactor is also modeled as 3x3 phase impedance matrix (self and mutual impedances) to consider mutual coupling among the phases of reactor if any. Normally these reactors do not have mutual coupling.

B. Steady State Analysis

Various simulation studies have to be conducted to select the initial value of NGR. Only steady state conditions have to be considered in these simulations. The various studies to be conducted are as follows,

1) Single pole switching

Single line to ground (SLG) faults account for 70%-95% of faults on EHV transmission lines and most of these are transitory in nature. From the stand point of minimizing the disturbances, especially loss of synchronism which may hamper the system stability caused by SLG fault, as well as to maintain reliability, it is desirable to clear them by opening only the circuit breaker pole on both terminals of the faulted phase out of the three phases and re-close after a certain time gap. This allows two energized and healthy phases to continue carrying power during the period of interruption, which has significant benefits. The increasing difficulty of construction of new EHV transmission lines as well as high cost makes the SPS an attractive method of achieving reliable power delivery system [5].

The network to be considered for steady state analysis is shown in Fig. 1 or 2 based on transmission line configuration. SLG fault is created at different locations viz., SS-A end, midpoint and SS-B end etc., with the NGR values varying from 0% to 100% of the phase reactor value. Single pole switching namely viz. opening of the single phase of the breakers at both the ends of circuit, is then carried out.

Values of the following parameters for different simulation cases are to be recorded.

- Steady state primary arc current
- Steady state secondary arc current
- Steady state recovery voltage
- Rate of Rise of Recovery Voltage (RRRV) in kV/ms after the SPS operation.
- Steady state neutral voltage and current for all the line reactors

2) Induced voltage during stuck breaker conditions

Open phase conditions may occur when line single-phase recloser is applied, or at the occurrence of stuck breaker poles in the opening or closing operation. Series resonance can occur in shunt compensated transmission lines during unbalanced switching operations resulting in open phase overvoltages that can damage line connected equipments and can therefore affect system security and availability. In open-phase condition a series resonance may occur with the coupling capacitance to the energized phases and large overvoltages may stress the open phases and associated open circuit breakers at their terminals [3].

EHV breakers are usually designed to operate with single pole mechanisms. It is possible that due to mechanical differences or defects, all three poles may not operate simultaneously or one of them can get stuck. One phase could be left open with the other two phases energized during stuck breaker condition while energizing the line or a single pole open condition arises while performing single pole reclosing. Similarly, two phases could be left open with the other phase energized during line de-energization. Shunt reactors increase the open-phase voltage considerably because of unequal compensation of the positive and zero-sequence line capacitances. As reactors are in parallel with the line conductor capacitance to ground, the equivalent phase-to-ground reactance at power frequency is inductive and may reach high value when the shunt compensation is large (above 65%). In such cases, parallel combination of the shunt reactor and the line shunt capacitance in series with the inter-phase capacitance forms a series resonant circuit. These conditions could result in series resonance on shunt compensated lines with attendant overvoltages and their detrimental effects on the connected equipments [6].

Steady state analysis of equivalent network model has to be performed for various simulated stuck breaker conditions.

Details of one stuck breaker condition to be simulated are as follows.

- Energize transmission line from SS-A to SS-B with one pole of SS-A end breaker with one pole stuck and keeping open all the three poles of breaker at SS-B end.
- Vary NGR value from 0% to 100% of phase reactor value.
- Record steady state open conductor(s) phase to ground voltage.
- Record steady state neutral voltage and current for all line shunt reactors.
- Observe whether there is any possibility of getting resonance at specific value of NGR.

Perform other stuck breaker simulated case studies.

3) Induced voltages on de-energized circuit

This study is applicable for only double circuit lines. A shunt compensated de-energized circuit running on the same right of way with an energized circuit can be subjected to high-induced voltages due to parallel resonance between the line shunt reactor and the line capacitance. The phenomenon of induced voltages, due to electrostatic and electromagnetic coupling, on a shunt compensated de-energized circuit from a parallel-energized circuit needs to be studied.

As the NGR is connected at the neutral point of the phase reactor, this may lead to a sustained oscillation in the ring down voltage on the de-energized circuit in a double circuit line. In the extreme case, depending upon the line length and degree of shunt reactive compensation on the line, resonating overvoltages may occur. Keeping this aspect in view the NGR value selected has to be examined for possible occurrence of resonating overvoltages.

Equivalent system to be considered for this induced voltage study is shown Fig. 2. Open all the three poles of circuit
breakers at both ends of one circuit and keep the other circuit in energized condition. Vary NGR value from 0% to 100% of phase reactor value.

For each NGR value the following values have to be recorded.

- Steady state phase to ground voltages of de-energized circuit.
- Steady state neutral voltage and current for all line shunt reactors.
- Observe whether there is any possibility of resonance for this value of NGR.

**C. Selection of initial NGR value:**

Based on the steady state analyses performed, the initial value of NGR is selected keeping in view the following two desired check conditions.

- Successful secondary arc extinction is normally expected for single/double circuit EHV line, if the secondary arc current is less than 40 A and the rate of rise of recovery voltage (RRRV) is less than 10 kV/msec [4]. The NGR value selected should satisfy these criteria.
- Based on the stuck breaker condition and induced voltages on de-energized circuit studies, examine whether there is any possibility of occurrence of resonance for the NGR value selected.

After checking that the NGR value selected satisfies both check conditions, transient analysis studies namely, energization, load rejection, single pole switching (open and reclose), and induced voltage studies are conducted. The rating of NGR is finalized based on the results of these studies.

**D. Transient Analyses**

1) **Single Pole re-closure study**

Equivalent system to be considered for the simulation is as per Fig. 1 or 2. Perform transient analysis study by creating SLG fault at various locations on the transmission line. Arc has to be modeled by variable fault conductance so that arc extinction is automatically controlled. Select suitable value for dead time to enable successful single pole re-closure [1], [2].

For each fault location the following waveforms have to be recorded.

- Secondary arc current
- Recovery voltage
- Neutral voltage and current for all the shunt reactors.

Observe the secondary arc extinction time and compare this with specified dead time to ensure successful re-closure.

2) **Temporary Overvoltage study (Load rejection and fault clearing)**

Other important parameters that are required to be specified for NGR design are continuous current rating, short time current rating, insulation level, etc. For determining the short time current rating and insulation level, transient studies are performed by simulating only load rejection, only SLG fault and load rejection accompanied with SLG fault.

For each case the following waveforms have to be recorded.

- Phase to ground voltages at SS-A and SS-B ends of transmission line
- Neutral voltage and current for all the shunt reactors.

Based on this study, select the insulation class, short time current rating and maximum peak current of the NGR.

3) **Switching Overvoltage Study**

Conduct line energization studies with selected NGR value to ensure that switching overvoltages are within acceptable limits considering trapped charges and line surge arresters. Check the energy class of surge arresters used.

4) **Induced voltages on de-energized circuit with selected NGR value (applicable for double circuit line)**

Perform the induced voltage study on second circuit (de-energized) by energizing the first circuit. Also conduct induced voltage studies on de-energized circuit by creating SLG fault on the energized circuit. Vary the MVAr value of the line reactor in +/-10% range. For example, for 80 MVAr line reactor vary the MVAr value of the line reactor from 72 to 88 MVAr in suitable steps. Also consider +/- 2.5% manufacturing tolerance for line reactor values amongst the phases.

For each case the following waveforms are to be recorded.

- Phase to ground voltages on de-energized circuit.
- Neutral voltage and current for all the line reactors.

Based on this study, determine the continuous current rating for NGR value selected.

**E. Summary of Studies**

Observations made from Summary of studies are presented in Table I.

<table>
<thead>
<tr>
<th>TABLE I. SUMMARY OF SYSTEM STUDIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Rated Impedance</td>
</tr>
<tr>
<td>Rated current and voltage</td>
</tr>
<tr>
<td>Continuous current and voltage</td>
</tr>
</tbody>
</table>
Rated peak current

Based on Transient analysis studies observe the maximum initial asymmetric peak current flowing through neutral.

Calculate the asymmetric peak current based on IEEE Std 32-1972.

Comparing these two values select the maximum to be the rated peak current for NGR.

Voltage class and Insulation level at neutral point.

Based on the steady state and transient analysis studies observe the maximum neutral voltage.

By using this value and referring to IEEE std. 32-1972 select the insulation class for NGR based fault voltage criteria.

Surge arrester rating for NGR

Duty cycle of surge arrester is chosen based on temporary overvoltage study or 10 second voltage rating.

Various parameters to be recommended for NGR rating are presented in Table III for a typical case study.

III. CASE STUDY

A. System Data

1) Equivalent network data

The equivalent source impedance data considered for study are presented in Table II.

<table>
<thead>
<tr>
<th>Equivalent Source Impedances</th>
<th>SS-A</th>
<th>SS-B</th>
</tr>
</thead>
<tbody>
<tr>
<td>R_s (Ω)</td>
<td>0.4</td>
<td>4.0</td>
</tr>
<tr>
<td>X_s (Ω)</td>
<td>8.0</td>
<td>80.0</td>
</tr>
<tr>
<td>R_0 (Ω)</td>
<td>2.0</td>
<td>20.0</td>
</tr>
<tr>
<td>X_0 (Ω)</td>
<td>24.0</td>
<td>160.0</td>
</tr>
</tbody>
</table>

2) Transmission line data

The 360 km, 400kV double circuit transmission line data considered for the study is presented in Fig. 3. Transposition for the transmission line is considered based on Fig. 2 and a shunt compensation of 80 MVAr has been considered at both ends of each circuit for the studies.

3) Surge arrester data

The 360 kV, class 4 surge arrester V-I characteristics are referred from [7].

B. Steady State Analysis

1) Single pole switching

Single pole switching study results for a typical case of a fault considered at the midpoint of the transmission line between substation A and B are presented in Figures 4 and 5. Similarly, studies need to be conducted for faults at different locations to arrive at the initial NGR rating.

From Figures 4 and 5, 30% NGR value gives recovery voltage of 40 kVrms, RRRV of 6.5 kV/ms and the secondary arc current of 20 Arms.

2) Stuck breaker condition

Different stuck breaker condition has been considered and simulated to arrive the initial NGR rating. Results of a typical stuck breaker condition as shown in Fig. 6 are presented in Figures 7 and 8.

From Figures 7 and 8, 30% NGR value gives recovery voltage of 40 kVrms, RRRV of 6.5 kV/ms and the secondary arc current of 20 Arms.
From Figures 7 and 8, 30% NGR value gives open phase voltage of 100 kVrms, neutral voltage of 76 kVrms and neutral current of 127 Arms.

3) Induced voltage

Studies regarding induced voltages on de-energized circuit have been simulated for different cases with the other circuit energized and with considering fault on the energized circuit at different locations. The simulation result for one typical case is presented in Fig. 9.

![Induced voltage on de-energized circuit](image)

From Fig. 9, 30% NGR value gives induced voltage on de-energized circuit 23 kVrms and 150 kVrms during normal and fault conditions respectively.

C. Section of Initial NGR Value

Based on literature [4], successful secondary arc extinction would apparently be expected for double circuit EHV line, if the secondary arc current is less than 40 A and the rate of rise of recovery voltage (RRRV) is less than 10kV/msec. Based on this reference and considering safety margin it is recommended to select NGR value as 30% of Xs, for successful secondary arc extinction. Also, from stuck breaker studies and studies regarding voltages induced on de-energized circuit, it is observed that the induced voltages are within acceptable limits for NGR value of 30%. Hence, initially an NGR value of 30% of Xs is selected and is considered for further studies namely, load rejection, switching, transient analysis-single pole reclosing, and induced voltages based on which NGR rating is finalized.

D. Transient Analysis

1) Single pole switching

Single pole switching study results for a typical case of a fault considered at the substation B are presented in Fig. 10. Similarly, studies need to be conducted for faults at different locations to finalize the NGR rating.

![Line Voltage Profiles during line energization](image)

From Fig. 10 (a), 30% NGR value gives the dead time of 250 ms, Fig.10 (b) shows the neutral current peak of 318 A. Fig.10(c) shows the maximum neutral voltage of 65 kVrms, based on IEEE Std.32 using fault voltage criteria 69 kVrms insulation class selected at neutral point.

2) Temporary Overvoltage study (load rejection)

Simple load rejection and load rejection accompanied with single line to ground fault were conducted on both ends of substations separately. Results of these studies are used for selection of surge arrester rating for protection of neutral reactor.

3) Switching Overvoltages

Switching overvoltage studies have been conducted for different operating conditions and the results for the same are presented in Fig. 11.
From Fig.11, it is observed that with 30% NGR and 360 kV surge arrester switching overvoltages are within limits.

4) **Induced voltage**

Studies regarding induced voltages on de-energized circuit have been simulated for different cases by varying the MVAr value of the line reactor in +/-10% range and +/- 2.5% manufacturing tolerance for line reactor values amongst the phases at different locations. The simulation results for the same are presented in Fig. 12.

From Fig.12, for selected 30% NGR value, induced voltages on de-energized circuit are within the limits of rated voltages. Neutral current of 2 Arms for normal condition used as one of the parameter to select the continuous rating for NGR.

E. **Recommended NGR Parameters**

Based on steady state and transient analyses studies the recommended NGR parameters are presented in Table III.

<table>
<thead>
<tr>
<th>TABLE III. RECOMMENDED NGR PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Recommended design rating for NGR</strong></td>
</tr>
<tr>
<td>Rated Impedance</td>
</tr>
<tr>
<td>Rated Current</td>
</tr>
<tr>
<td>with other circuit energized</td>
</tr>
<tr>
<td>Rated Voltage</td>
</tr>
<tr>
<td>with fault on energized circuit</td>
</tr>
<tr>
<td>Rated peak current</td>
</tr>
<tr>
<td>Rated Power</td>
</tr>
<tr>
<td>for 10 seconds</td>
</tr>
<tr>
<td>Rated Frequency</td>
</tr>
<tr>
<td>Rated Insulation Class at neutral point</td>
</tr>
<tr>
<td>Minimum BIL value at neutral point of</td>
</tr>
<tr>
<td>reactor</td>
</tr>
<tr>
<td>Minimum BIL value at neutral bushing of</td>
</tr>
<tr>
<td>reactor</td>
</tr>
<tr>
<td>No. of Phases</td>
</tr>
<tr>
<td>Connection</td>
</tr>
<tr>
<td>Insulation class at earthing side</td>
</tr>
<tr>
<td>BIL Earthing Side</td>
</tr>
<tr>
<td>Temperature Rise</td>
</tr>
<tr>
<td>Surge Arrester, class</td>
</tr>
</tbody>
</table>

IV. **CONCLUSIONS**

Shunt reactors are generally provided on long EHV transmission lines to limit overvoltage during line energization and load rejection. Use of neutral grounding reactor at the neutral point of the shunt reactor on long EHV lines is judiciously adopted to ensure the secondary arc extinction and successful single pole switching as 80% of the transient faults on EHV lines are single line to ground fault. This paper provides the guidelines to properly rate the NGR for the steady state and transient duties to which they will be exposed by determining the NGR parameters initially based on steady state analysis and finalizing the ratings by performing transient analysis with arc modeling and arc extinction time.

**REFERENCES**


