



## Enhancing Transmission Reliability through Reactive Power Compensation: An ETAP-Based Case Study of the NEPS-SEPS Line in Afghanistan

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### Abstract

Long-distance AC transmission lines in Afghanistan, such as the 578 km North East Power System to South East Power System (NEPS-SEP) connector, face severe voltage drops and stability issues due to reactive power imbalances. This study investigates the role of reactive power compensation (RPC) in enhancing voltage stability and reducing power losses along this corridor. Using the Newton-Raphson load flow analysis implemented in ETAP, the system was modeled under full load, 50% load, and light load conditions. The findings reveal voltage drops of up to 16% at critical substations under full load, necessitating strategic deployment of mechanical switch capacitors (MSCs), reactors (MSRs), and static VAR compensators (SVCs). Optimized RPC configurations are proposed, showing improved voltage regulation within  $\pm 5\%$  and reduced system losses. These results demonstrate that appropriate RPC planning is essential for the reliability and efficiency of Afghanistan's power transmission infrastructure.

### Keywords

ETAP Simulation; Grid Reliability; NEPS-SEPS Connector; Reactive Power Compensation; Static VAR Compensator; Transmission Line Losses

## بهبود قابلیت اطمینان خطوط انتقال از طریق جبران توان غیرفعال: یک مطالعه موردی مبتنی بر ETAP از خط NEPS-SEPS در افغانستان

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### چکیده

خطوط انتقال جریان متناوب بلندمسافت در افغانستان، مانند خط اتصال ۵۷۸ کیلومتری NEPS-SEPS، به دلیل عدم تعادل توان راکتیو با کاهش شدید ولتاژ و مشکلات پایداری مواجه هستند. این مطالعه نقش جبران توان راکتیو (RPC) را در بهبود پایداری ولتاژ و کاهش ضایعات توان در طول این مسیر را بررسی می‌کند. با استفاده از تحلیل جریان بار نیوتن-رافسون که در نرم‌افزار ETAP پیاده‌سازی شده است، سیستم تحت شرایط بار کامل، ۵۰٪ و بار کم مدل‌سازی شده است. نتایج نشان می‌دهد که در بار کامل، کاهش ولتاژ تا ۱۶٪ در سب استیشن‌های مهم رخ می‌دهد که نیازمند شدید استفاده از خازن‌های سویچ‌کننده مکانیکی (MSC)، راکتورها (MSR) و جبران‌کننده‌های استاتیک VAR (SVC) است. ساختارهای بهینه جبران توان راکتیو ارائه شده که تنظیم ولتاژ را در محدوده  $\pm 5\%$  بهبود داده و ضایعات سیستم را کاهش می‌دهد. این نتایج نشان می‌دهد که برنامه‌ریزی مناسب RPC برای اطمینان و کارایی زیربنای انتقال برق افغانستان ضروری است.

واژه‌های کلیدی: جبران توان راکتیو؛ شبیه‌سازی ETAP؛ جبران‌کننده استاتیک VAR؛ ضایعات خطوط انتقال؛ قابلیت اطمینان شبکه؛ خط

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## Introduction

Interconnection of regional power grids has become a global trend due to its economic and security benefits (Wu et al., 2012). Large power systems can be interconnected using either AC or DC links (Wu et al., 2012). Since most existing networks are AC-based, AC interconnection remains a practical and economically justified choice (Clark et al., 2008). However, extensive AC interconnections can increase system complexity and may negatively affect stability and reliability, whereas DC links can improve operational controllability and reliability (Zhang et al., 2011). Despite these advantages, replacing prevailing AC infrastructure with DC links is often not feasible or cost-effective in many contexts (Imdadullah et al., 2020).

Transmission systems must operate reliably to deliver power efficiently over long distances. In modern interconnected networks, stability issues, particularly voltage stability, are a major concern (Shuchuang, 2015; Tang, 2021). System stability broadly refers to the ability to return to an acceptable operating condition following a disturbance, which is essential for secure and reliable grid operation (Abdul & Shabana, 2013; Tang, 2015). Practical mitigation measures are therefore required to address voltage deviations and associated operational risks in both normal and disturbed conditions (Maheshkumar, 2016).

Among available measures, reactive power compensation (RPC) is widely used to support voltage regulation and reduce transmission losses by managing reactive power flow and improving voltage profiles at critical buses (Ahmed et al., 2017; Stanley & Oniyeburutan, 2023). Depending on system needs, compensation can be implemented using technologies such as capacitor/reactor banks and dynamic devices (e.g., SVC) (Matias, 2013). Prior studies have also shown that dynamic compensators such as static VAR compensators (SVCs) can be preferable to fixed capacitors/inductors for voltage control in large transmission systems (Chopade et al., 2011). In this study, RPC options considered in practice include mechanical switched capacitors/reactors and dynamic compensation through SVC, consistent with common implementations in transmission networks (Dixon et al., 2005; Maheshkumar, 2016).

This paper focuses on Afghanistan's transmission context, where the power sector faces persistent structural and operational constraints, including high transmission losses, reliance on imported electricity, an asynchronous national grid, and planning and implementation limitations (Mohsin & Bernell, 2018; Ahmadzai & McKinna, 2018). Afghanistan's grid consists of multiple islanded subsystems supplied through different external sources, which limits system-wide operational flexibility (Mohsin & Bernell, 2018). Asynchronous operation also constrains efficient interconnection and power trade, and a unified national grid would require appropriate conversion solutions such as back-to-back stations (Fichtner & Co. KG, 2013; Ahmadzai & Mckinna, 2018).

Within this setting, the NEPS–SEPS connector is a long double-circuit 220 kV corridor that links major load centers and intermediate substations, extending 578 km from Chimtala (Kabul) to Kandahar East and supplying Kabul and other regional loads (Shambalid et al., 2020; SIGAR, 2016). Long-distance AC transmission along this corridor contributes to low bus voltages and power oscillations, which may occur during normal operation and under contingencies such as faults (Shambhali et al., 2020; SIGAR, 2016). To determine the compensation infrastructure required to maintain acceptable voltage conditions and reduce losses, this study uses load flow analysis to establish the steady-state operating condition and guide the sizing and placement of compensation devices (Salomon et al., 2013).

Accordingly, the objective of this study is to determine the reactive power compensation requirements for the NEPS–SEPS connector to:

- Improve power quality,
- Maintain bus voltages within  $\pm 5\%$  of rated values, and
- Reduce corridor losses under representative operating conditions. The remainder of the paper presents the methodology and load-flow-based evaluation, followed by findings, discussion, and conclusions.

## **Methodology**

In this case study, the analysis is limited to the NEPS–SEPS connector: the proposed 578 km high-voltage transmission line from the Chimtala substation (Kabul) to the Kandahar East substation (Kandahar), including the intermediate 220 kV/20 kV substations along the route. The study

evaluates three operating conditions: maximum line loading of 211.8 MVA, 50% loading, and 20% loading at Chimtala, based on the USAID contract design documents. The purpose is to identify the reactive power compensation (RPC) infrastructure needed to reduce voltage fluctuations and improve system stability during normal operation and during switching, fault clearing, and contingency conditions.

To design an appropriate RPC scheme, load-flow analysis is performed to keep bus voltages within the specified limits, reduce transmission losses, and maintain reliable operation under disturbances. The required system data are gathered from surveys, the NEPS–SEPS design documents, and materials provided by USAID, the Ministry of Energy and Water (MEW), Da Afghanistan Breshna Sherkat (DABS), relevant companies, and prior studies. These documents and specifications are reviewed and cross-checked to confirm the network's current condition and validate the dataset. In addition, site visits and interviews with substation operation staff along the corridor are conducted to record the necessary field information. The overall data collection and ETAP-based analysis process is illustrated in Figure 1, and the key system characteristics and design loading assumptions used for RPC design are summarized in Table 1.

ETAP is used as the simulation platform for this study because it provides practical, power-system analysis and management capabilities for generation, transmission, and distribution networks. In this work, ETAP is applied specifically to perform the power-flow analysis of the NEPS–SEPS connector under the required operating scenarios.

Load-flow analysis is conducted to examine the NEPS–SEPS system at different loading levels and to evaluate its steady-state performance (Abdul & Shabna, 2013). It also supports key planning and assessment needs, including optimal load distribution, unit deployment, contingency planning, transient analysis, and short-circuit studies (Raheel et al., 2019). The analysis is based on the per-unit system and a single-line representation, using the standard load-flow variables: bus voltage magnitude ( $V$ ), voltage angle ( $\delta$ ), active power ( $P$ ), and reactive power ( $Q$ ). Table 2 summarizes the known and unknown parameters for the three bus types used in the load-flow study.

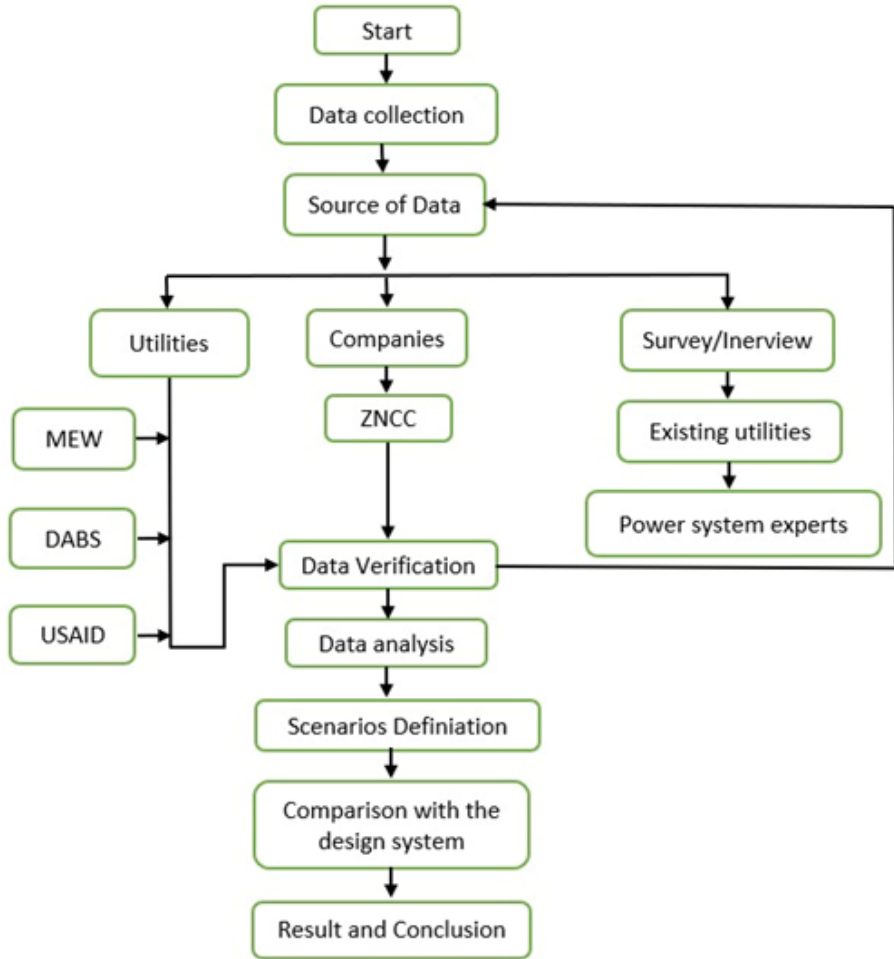


Figure 1: Data collection and analysis process flow chart.

Table 1. The NEPS-SEPS Transformers and load information

Transformers and Load Information for Full-load study			
Substation Location	Distance from preceding substation	Substation transformer capacity	RPC Design Load
Chimtala	Start Point	2Tx160MVA (220/110KV)	2x10MVAR (CAP) 1x20MVAR (CAP) 1x40MVAR (CAP) 1x25MVR (Reactor) +30/-140MVAR (SVC)
Arghandi	26.60Km	1Tx60MVA (220/20KV) 1Tx50MVA (220/110KV)	50.7MVR

Sayed Abad	63.20Km	2T×10MVA	2x15MVAR (Reactor)
Ghazni	82.75Km	3T×10MVA	2x15MVAR (Reactor)
Qarabagh	55.20Km	2T×10MVA	
Moqor	63.95Km	2T×10MVA	
Shohjoy	69.31Km	2T×10MVA	
Qalat	84.63Km	2T×10MVA	
Kandahar East	132.35Km	2T×30MVA	1x20MVAR (CAP)
		(220/20KV)	2x10MVAR (CAP)
		2T×80MVA	2x25MVAR (Reactor)
		(220/110KV)	+40/-40MVAR (SVC)
<b>Total</b>	577.99Km	780 MVA (350MVA in SEPS Portion and 430MVA Kabul load)	305.7MVAR

Table 2. Type of bus in load flow analysis

Type of Bus	Specified Quantities	Calculated Quantities
Generator Bus (PV Bus)	Real power (P)	Reactive power (Q)
	Voltage magnitude (V)	Voltage angle ( $\delta$ )
Load Bus (PQ Bus)	Real power (P)	Voltage magnitude (V)
	Reactive power (Q)	Voltage angle ( $\delta$ )
	Voltage magnitude (V)	Real power (P)
Slack Bus	Voltage angle ( $\delta$ )	Reactive power (Q)

Several load-flow solution techniques are available, including the Gauss–Seidel, Newton–Raphson, and fast-decoupled methods (Meshram & Gawande, 2017). In this study, the Newton–Raphson approach is selected because it provides high accuracy and typically converges in fewer iterations, and thus less computation time than Gauss–Seidel. Newton–Raphson is a well-established iterative algorithm in power-flow studies, using a Taylor-series expansion to linearize the nonlinear simultaneous equations of the load-flow problem (Kulworawanichpong, 2009; Raheel et al., 2019). Accordingly, for voltage-control (PV) buses where active power and voltage magnitude are specified, the power-flow equations are formulated in polar form as presented in (Saadat, 1999).

The real and reactive power at bus  $i$  is:

$$P_i + Q_i = V_i I_i^* \quad (1)$$

$$I_i = \frac{P_i + Q_i}{V_i^*} \quad (2)$$

The bus admittance matrix could be used to express the aforementioned equation as follows:

$$I_i = \sum_{j=1}^n |Y_{ij}| |V_{ij}| \angle(\theta_{ij} + \angle\delta_j) \quad (3)$$

$$P_i - jQ_i = (|V_i| \angle - \delta_i) \sum_{j=1}^n |Y_{ij}| |V_{ij}| \angle(\theta_{ij} + \delta_j) \quad (4)$$

Equation (4)'s real and imaginary parts are separated as follows:

$$P_i = \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \quad (5)$$

$$Q_i = - \sum_{j=1}^n |V_i| |V_j| |Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \quad (6)$$

With respect to the independent variables, namely voltage magnitude in per unit and phase angle in radians, equations (5) and (6) form a collection of nonlinear algebraic equations. For each voltage-controlled bus, we have one equation given by (5); for each load bus, we have two equations provided by (5) and (6). The following set of linear equations is obtained by expanding the aforementioned equations in Taylor's series (Kulworawanichpong, 2009).

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_2} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \vdots \\ \Delta \delta_2^{(k)} \\ \vdots \\ \vdots \\ \Delta |V_2^{(k)}| \\ \vdots \\ \vdots \\ \Delta |V_n^{(k)}| \end{bmatrix} \quad (7)$$

In equation (7), Bus-1 is taken to be the slack bus. The linearized relationship between slight variations in real ( $\Delta P(k)$ ) and reactive ( $\Delta Q_i(k)$ ) power and slight variations in voltage angle ( $\Delta \delta_i(k)$ ) and voltage

magnitude ( $\Delta|Vn(k)|$ ) is provided by the Jacobian matrix. The partial derivatives of equations (5) and (6), evaluated at  $\Delta\delta(k)$  and  $\Delta|Vn(k)|$ , are components of the Jacobian matrix. In brief, it can be expressed as follows (Saadat, 1999):

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \quad (8)$$

The voltage magnitudes of voltage-controlled buses are known. Consequently, the  $m$  equation including  $\Delta Q$  and  $\Delta V$ , as well as the associated columns in the Jacobian matrix, are deleted if the system's  $m$  buses are voltage-controlled. Once we performed algebraic operations on the Jacobian matrix for the diagonal and off-diagonal of  $J_i$  element, we can derive the following equation for the terms  $\Delta P_i^{(k)}$  and  $\Delta Q_i^{(k)}$ . What are the differences between the schedule and computed values:

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \quad (9)$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \quad (10)$$

The new approximations for bus voltage are:

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \quad (11)$$

$$\left| V_i^{(k+1)} \right| = \left| V_i^{(k)} \right| + \Delta \left| V_i^{(k)} \right| \quad (12)$$

The following is the method for power flow solution using the Newton-Raphson method:

1. Where  $P_i^{sch}$  and  $Q_i^{sch}$  are provided for load buses, the voltage magnitudes and phase angles are set to either 1 or 0 (the slack bus values) i.e.,  $\left| V_i^{(0)} \right| = 1$  and  $\delta_i^{(0)} = 0$ .
2. Where  $|V_i|$  and  $P_i^{sch}$  are specified for voltage-regulated buses, phase angles are assigned equal to the slack bus angle or 0, i.e.,  $\delta_i^{(0)} = 0$ .
3.  $P_i^{(k)}$  and  $Q_i^{(k)}$  are evaluated from (5) and (6) and  $\Delta P_i^{(k)}$  and  $\Delta Q_i^{(k)}$  are calculated from (9) and (10) for load buses.
4.  $P_i^{(k)}$  and  $\Delta P_i^{(k)}$  are computed from (5) and (9), for voltage-controlled buses, respectively.
5. Gaussian elimination and optimally ordered triangular factorization are used to directly solve the linear simultaneous equation (8).

6. Using (11) and (12), the new voltage magnitudes and phase angles are calculated.
7. Continue the process until the residuals  $\Delta P_i^{(k)}$  and  $\Delta Q_i^{(k)}$  are less than the specified accuracy, i.e.,

$$\left| \Delta P_i^{(k)} \right| \leq \varepsilon \quad (13)$$

$$\left| \Delta Q_i^{(k)} \right| \leq \varepsilon \quad (14)$$

The NEPS-SEPS connector operated as double circuit analysis is performed as:

- Evaluation of the NEPS-SEPS connector energization
- PQ (Real Power-Reactive Power)
- PV (Real Power-Voltage)
- QV (Reactive power-voltage) analysis
- Contingency

Each analysis is conducted to support the selection of RPC size and placement under realistic operating constraints. This includes accounting for system operating conditions, the reduced marginal benefit of adding higher levels of compensation, practical RPC limits for achieving maximum steady-state power transfer to the Kabul area while supplying the NEPS–SEPS connector load, and the allowable additional load that can be imported into the NEPS–SEPS connector substations. The load study follows the system requirements defined in the NEPS–SEPS connector design documents.

To identify worst-case conditions and verify the robustness of the selected RPC, multiple contingencies are evaluated, assuming the NEPS–SEPS connector operates as a double-circuit. These contingency cases are used to further define the additional load that can be imported from the north to Kabul and to test the SVC performance under five operating conditions, noting that the electrical designer’s load study considered three conditions and that these sets of conditions are not the same:

- Loss of 60MVAR Chimtala substation 110KV MSC
- Loss of one circuit of the Chimtala to Arghandi

- Loss of 220KV load at Kandahar East Substation
- Loss of 220KV load at Qarabagh
- Loss of 220KV load at Moqor
- Loss of 220KV load at Shah Joy
- Loss of 220KV load at Qalat

For each system configuration and import level, the power-flow results under operating and contingency conditions are reviewed, and the MSC/MSR sizes are adjusted as needed to eliminate voltage violations.

The operating limits used for this design reflect what can be achieved in practice with a properly applied RPC scheme and standard voltage-limit expectations. The goal is to define a robust RPC requirement that enables system operators to improve overall performance and support higher import levels, while recognizing that, based on operational experience, the utility will ultimately establish its own detailed operating practices and voltage-limit settings.

- Steady-state Normal system -0.95 to 1.05 per unit on 110KV and 220KV main buses
- Steady-state Voltage after a not catastrophic contingency -0.95 to 1.1 per unit on 110KV and 220KV buses.
- Steady-state voltage change resulting from switching MSCs or MSRs- No greater than 3% increase or decrease (achievable through switching one or more MSCs in combination).

## **Results**

The steady-state power-flow results for full-load and light-load conditions of the NEPS-SEPS connector are summarized in Tables 3 and 4. For the light-load case, voltage rise is observed (Table 4). Based on these results, the system requires MSC installation at Kandahar East, Qalat, Shoh Joy, Moqor, and Qarabagh substations to maintain secure and stable operation.

Table 3. Voltage drops in full load in the NEPS-SEPS connector

Substation Location	Voltage drops in full load (without MSC)
Kandahar East	16%
Qalat	12%
Shoh Joy	10%
Moqor	8%
Qarabagh	7%

Table 4. Voltage rises in Light load in the NEPS-SEPS connector

Substation Location	Voltage rises in light load (without MSC)
Kandahar East	2.35%
Qalat	3.64%
Shoh Joy	3.83%
Moqor	3.60%
Qarabagh	3.10%

Table 5 tabulated voltage conditions in the located substations in the NEPS-SEPS connector after we added the recommended MSRs and MSCs as per the load flow study results to the system. Therefore, to absorb some of the reactive power supplied by the line, fewer reactors are needed in light load conditions.

Table 5. Recommended MSRs and MSCs base on the load flow study for the NEPS-SEPS connector

Location	Type	Quantity	Rating	Type	Quantity	Rating
Qarabagh Substation	MSR	1	20MVAR	MSC	1	10MVAR
Moqor Substation	MSR	1	20MVAR	MSC	1	10MVAR
Shoh Joy Substation	MSR	1	20MVAR	MSC	1	10MVAR
Qalat Substation	MSR	1	30MVAR	MSC	1	20MVAR
Kandahar East Substation	MSR	1	20MVAR	MSC	1	40MVAR

Table 6 summarizes the additional MSRs and MSCs recommended for the NEPS–SEPS connector, alongside the RPC equipment already specified in the design documents, to address both voltage drop and voltage rise along the corridor.

Table 6: The NEPS-SEPS connector MSRs and MSCs and voltage in light and full load

Substation Location and Voltage Rating	Light Load		Full Load	
	Recommended MSRs	Voltage (per unit)	Recommended MSCs	Voltage (per unit)
Arghandi 220kV	0	1.034	0	1.03
Sayed Abad 220kV	0	1.031	0	1.036
Ghazni 220kV	0	1.027	0	1.040
Qarabagh 220kV	One 20MVAR	1.026	One 10MVAR	1.039
Moqor 220kV	One 20MVAR	1.023	One 10MVAR	1.036
Shoh Joy 200kV	One 20MVAR	1.020	One 10MVAR	1.031
Qalat 220kV	One 30MVAR	1.014	One 20MVAR	1.022
Kandahar East 220kV	One 20MVAR	1.00	One 40MVAR	1.00

## Discussions

Load-flow analysis is carried out to determine the appropriate sizes and locations of reactive power compensation (RPC) equipment required to keep the NEPS–SEPS connector operating securely and stably. Under the half-load (50% transformer loading) case, the NEPS–SEPS system becomes unstable; therefore, mechanical switched capacitors (MSCs) and mechanical switched reactors (MSRs) are not considered necessary for that operating condition, as summarized in Table 6.

At Kandahar East, the proposed MSC and MSR are intended to support the network under full-load and light-load conditions; accordingly, the 40 MVAR MSC suggested for Kandahar East is separate from the SVC system. In contrast, the MSC installed on the 220 kV side of the SVC is intended to provide rapid reactive power support for the high-voltage transmission line. Because the designed RPC values and the recommended MSC at Kandahar East differ, the RPC design for this substation should be rechecked to confirm whether the original design or the recommended compensation should be adopted.

Reactive power compensation aims to manage reactive power effectively to improve the overall performance of AC power networks, and it is commonly addressed from two main aspects:

- Support for voltage and load compensation. Enhancing power factor, balancing actual power drawn from the source, improving voltage control, and other aspects of big fluctuating loads are all examples of load compensation.
- The goal of voltage support is to reduce voltage fluctuations at a certain transmission line terminal.

Reactive power is consumed in transmission systems due to line impedance and the need for lagging VAR support by most generating machines, which reduces stability margins for both the network and transmission lines. When this reactive demand is not properly managed, excessive voltage drops occur, increasing losses that must be supplied by the source, placing additional stress on the system and potentially contributing to line interruptions.

Accordingly, reactive power compensation helps mitigate these impacts and also improves the system's transient response during faults and disturbances. In this study, load-flow analysis is used to assess operating conditions and to identify the appropriate locations and sizes of compensation devices required to achieve better overall system performance.

The steady-state criteria used for RPC analysis were: voltage along the NEPS-SEPS line from Chimtala substation to Kandahar East substation must be between 0.95 and 1.05 per unit under intact system light load (20% of load, that is, 73.1 MW of load in Kabul area and 59.4 MW in NEPS-SEPS) and full load (350MVA in SEPS-NEPS and 430MVA in Kabul area). Steady-state power flow analysis, including QV analysis, were performed to determine recommended MSC location, size and step size.

Under full-load operation, the NEPS–SEPS system experiences significant voltage drop along the corridor. Table 3 shows a drop of 16% at Kandahar East, 12% at Qalat ( $\approx 372$  km from Chimtala), 10% at Shoh Joy ( $\approx 303.6$  km), 8% at Moqor ( $\approx 243.3$  km), and 7% at Qarabagh in Ghazni ( $\approx 190$  km). As illustrated in Figure 2, these drops exceed standard limits, with the most

severe conditions occurring at Kandahar East, Qalat, and Shoh Joy, indicating the need for RPC in this operating case based on the load-flow results.

Without adequate compensation, the system may face voltage collapse or voltage levels severe enough to require load tripping to protect equipment during certain contingencies, such as faults on import transmission lines or major substation buses. The proposed RPC design is intended to reduce these operational risks, though it does not eliminate them completely.

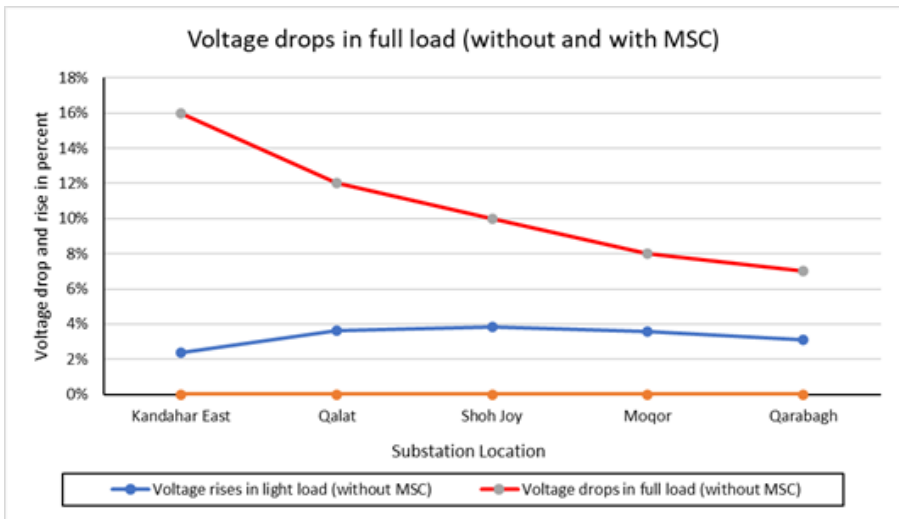


Figure 2: Voltage drops in full load condition of the NEPS-SEPS connector power system

The proposed RPC scheme is intended to regulate voltage under intact system conditions by providing automatic, continuously variable reactive power support through the SVC. With the NEPS–SEPS connector operating as a double circuit, the SVCs at Chimtala and Kandahar East, together with the RPC equipment at intermediate substations, are expected to keep the steady-state voltage within a preset bandwidth at the Chimtala 220 kV bus and across all corridor substations, as shown in Figure 3.

In addition, the RPC system is designed to help the network ride through severe operating events that could otherwise lead to instability. These include the loss of the largest transformer under heavy-load conditions at Chimtala, Arghandi, Kandahar East, or intermediate substations; increased loading due to transmission segment outages within

the NEPS system; and the loss of the largest MSC or MSR banks during heavy loading. The MSC and MSR step sizes are selected to be small enough to provide operational flexibility while maintaining voltage control.

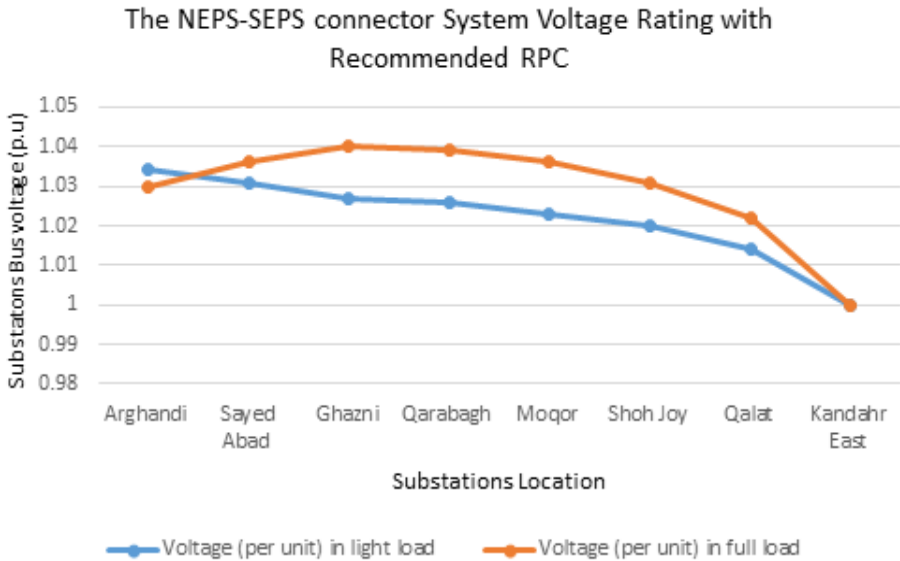


Figure 3: Voltage rating (p.u) in light and full load condition of the NEPS-SEPS connector power system.

Installing two 10 MVAR MSCs on the Chimtala 110 kV buses and two 10 MVAR MSCs on the Kandahar East 220 kV buses (one per bus) offers two practical advantages. First, switching these MSCs allows the SVC to operate closer to zero reactive power, preserving SVC capacity for disturbance management. Second, the smaller step sizes give operators better voltage control if an SVC is out of service, enabling MSC switching in smaller increments, about 3% voltage change, by using one capacitor or combinations of capacitors.

Managing reactive power exchange between the NEPS–SEPS connector and the Chimtala 220 kV bus is therefore a key operational issue. If the SVC is unavailable and the reactive power flow criteria between Chimtala and Arghandi are violated, the Chimtala voltage can be significantly affected. Even when the Chimtala SVC is in service, violating this reactive power flow criterion pushes the SVC away from its preferred near-neutral operating bandwidth.

The MSC installed on the 220 kV side of the SVC is intended to provide rapid-acting reactive power support for the high-voltage transmission grid. In contrast, the proposed MSC and MSR at Kandahar East are meant to address the network's full-load and light-load operating cases; therefore, the recommended 40 MVAR MSC at Kandahar East is independent of the SVC system. Because the designed RPC values differ from the recommended MSC at Kandahar East, the MSCs and MSRs listed in Table 5 are recommended to ensure the system operates within the steady-state voltage range of 0.95–1.05 p.u.

### **Conclusion**

This study confirms that reactive power compensation is essential for reducing voltage instability and excessive losses in long-distance transmission corridors such as Afghanistan's NEPS–SEPS connector. The recommended combination of MSCs, MSRs, and SVCs—selected for specific substations and loading conditions, supports keeping bus voltages within the required limits under a range of operating and contingency scenarios. In doing so, the proposed scheme improves overall reliability and increases the corridor's ability to transfer load between regions. Future work should focus on dynamic, real-time reactive power control using advanced FACTS devices and evaluate the economic trade-offs among RPC options as Afghanistan's power system continues to develop.

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### **Author Contributions**

Conceptualization, Rafiullah Wardak, and Habiburrahman Shirani; methodology, Rafiullah Wardak and Zahidullah Oriakhail; software,

Rafiullah Wardak and Zahidullah Oriakhail; validation, Mohammad Shafi Sharifi, Habiburahman Shirani and Zahidullah Oriakhail; formal analysis, Rafiullah Wardak; investigation, Rafiullah Wardak and Habiburahman Shirani; resources, Rafiullah Wardak; writing—original draft preparation, Rafiullah Wardak and Zahidullah Oriakhail; visualization, Habiburahman Shirani; supervision, Habiburahman Shirani, Mohammad Shafi Sharifi; project administration, Habiburahman Shirani

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