Fast-decoupled power flow optimization in 20 kV systems

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ABSTRACT

Power flow optimization in electrical power distribution systems is crucial for maintaining voltage stability and energy efficiency. 20 kV distribution systems often face voltage profile instability issues due to high power losses, where conventional power flow analysis methods are sometimes inefficient in handling load fluctuations in medium-voltage networks. This study proposes power flow calculation optimization using the fast-decoupled approach to evaluate and improve voltage profiles quickly and accurately, as well as integrating reactive power compensation through strategic capacitor bank placement. Simulation results show that under existing conditions, the system experiences significant voltage drops, especially at Bus 27 (17.740 kV) and Bus 53 (7.640 kV). After implementing a 2×900 kVAr capacitor bank, the voltage profile increased dramatically: Bus 27 rose to 19.160 kV and Bus 52 reached 19.020 kV. This proves that the integration of the fast-decoupled method and reactive power compensation is effective in minimizing voltage deviation and improving the operational stability of the distribution system.

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1. INTRODUCTION

The reliable and efficient operation of electrical power systems is essential to meet the growing demand for electricity and to maintain the stability of national grids. In medium-voltage networks, particularly those operating at 20 kV, accurate power flow analysis is crucial for system planning, operation, and real-time monitoring. Power flow studies provide valuable insights into voltage profiles, power losses, load conditions, and system constraints, enabling engineers to make informed decisions to ensure optimal network performance [1]. Conventional approaches to power flow analysis include methods like Gauss-Seidel and Newton-Raphson, have been widely used in the industry due to their robustness and accuracy. However, as power systems grow in complexity and scale driven by factors such as distributed generation, electric vehicle integration, and smart grid implementation these conventional methods often face limitations in terms of computational efficiency and convergence time. This becomes a critical issue in medium-voltage distribution systems, where fast and frequent calculations are needed to maintain real-time operational control and dynamic load balancing [2], [3].

Modern 20 kV distribution networks face significant operational hurdles, primarily characterized by severe voltage drops and instability during peak loading. In the studied system, critical deviations were identified at Bus 27 (17.740 kV) and Bus 53 (7.640 kV). These conditions not only breach standard operational margins but also lead to increased power losses and a high risk of localized system collapse, necessitating an immediate and effective mitigation strategy. A viable substitute is the fast-decoupled load flow (FDLF) technique. This approach is a modified form of the Newton-Raphson method that simplifies the

Jacobian matrix by decoupling the real and reactive power equations, thus reducing the computational burden significantly. Several recent studies [4], [5] have suggested that the FDLF method assumes weak coupling between active power and voltage magnitude, and between reactive power and voltage angle an assumption generally valid in high-voltage and medium-voltage systems.

Standard power flow analysis methods, such as the conventional Newton-Raphson, often encounter challenges in distribution systems due to their high R/X ratios and the computational burden required for large-scale iterations. There is a persistent need for a more computationally efficient approach that can decouple active and reactive power components to speed up convergence without sacrificing the accuracy required for high-voltage (20 kV) network modeling. Power flow calculation has traditionally employed methods such as the Newton-Raphson approach, although highly accurate, can be computationally intensive, especially for large or complex systems [6], [7]. By applying this technique, the study seeks to contribute to more effective planning and operation of distribution networks, supporting the broader objective of enhancing the reliability and efficiency of electrical energy systems [8], [9].

Several recent studies [10], [11] have suggested that the primary objective of this research is to optimize the voltage profile of a 20 kV system through the strategic integration of the fast-decoupled power flow or FDPF algorithm and reactive power compensation. The optimization process also seeks to fine-tune the implementation of the FDLF method to suit the specific characteristics of a 20 kV system, including line impedances, load variability, and network topology [12]. By implementing the fast-decoupled method in power flow calculations for 20 kV systems, this research is expected to contribute to faster decision-making processes, better voltage stability, and enhanced energy distribution efficiency. Several recent studies [13], [14] have suggested that the findings of this study may also serve as a reference for utility companies and system operators in adopting more advanced and efficient algorithms for distribution network analysis and control.

An electric power system consists of four primary components: generation, transmission, distribution, and load (end users). Electrical energy is generated and then transferred to transmission lines via a step-up transformer. From there, the power moves through the transmission network to the distribution system, which finally delivers electricity to consumers [15], [16]. An illustration of the electric power system is provided in Figure 1.

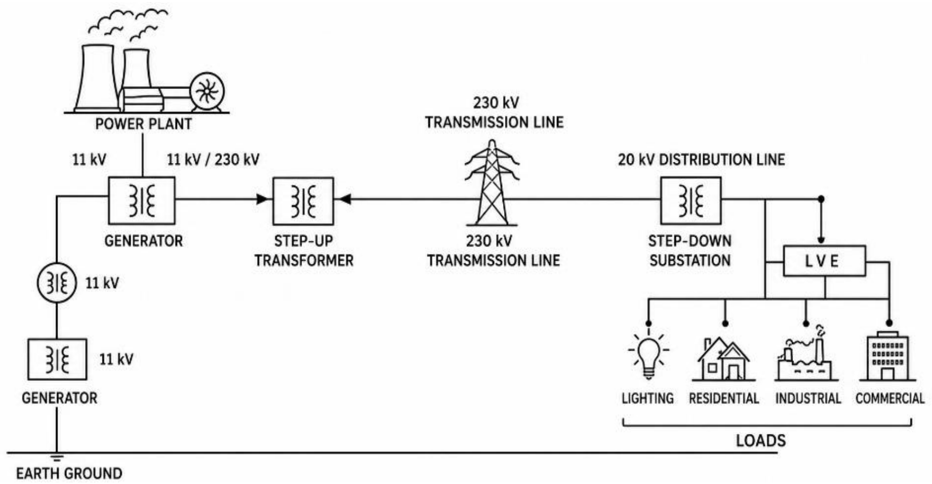

Figure 1. System of electric power

Figure 1 shows that the electric power system is an integrated system that functions to generate, transmit, and distribute electrical energy from the source of generation to consumers (loads) in a reliable, safe, and efficient manner. This system consists of three main parts, namely generation, transmission, and distribution. At the generation stage, electrical energy is produced from various energy sources such as water, steam, gas, coal, and renewable energy, then the voltage is increased for transmission efficiency [17].

In its operation, the distribution system will eventually be loaded up to its maximum capacity in line with load growth. The distribution system consists of three types of networks: radial, spindle, and loop. A radial network is a system that has a single power source supplying all loads along one path, Several recent studies [18]–[20] have suggested that a spindle network is a system that has more than one source supplying the loads, but still in a branched configuration, a loop network is a system that consists of multiple power sources that are interconnected, forming a closed loop for enhanced reliability and flexibility. With technological developments, distribution systems continue to evolve towards smart distribution systems to improve the efficiency and reliability of electricity services. In its operation, the distribution system will eventually be loaded up to its maximum capacity in line with load growth [21], [22]. The electrical power distribution system is shown in Figure 2.

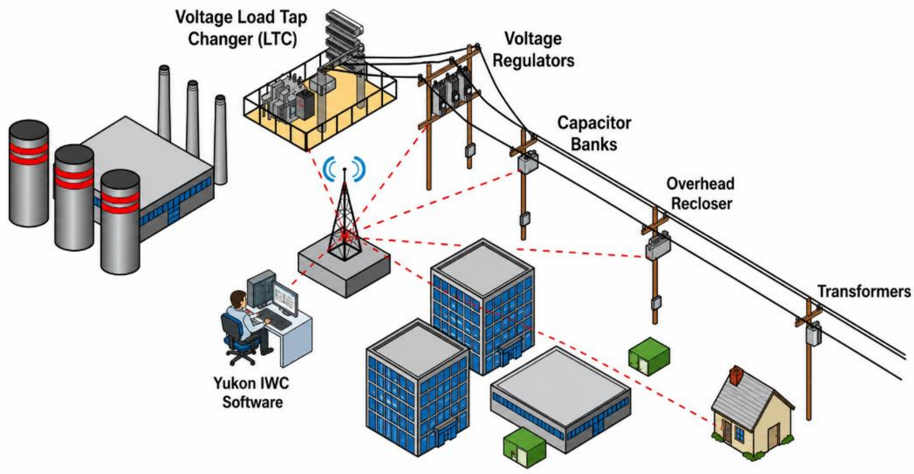

Figure 2. The electrical power distribution system

Figure 2 shows that the electrical power distribution system is the final part of the electrical power system that functions to distribute electrical energy from the substation to consumers at the appropriate voltage level. This system plays an important role in determining the quality, reliability, and continuity of electricity service. Based on voltage level, the distribution system consists of medium voltage distribution and low voltage distribution.

2. METHOD

This research employs the fast decouple power flow method to improve voltage drop and power losses by placing optimal capacitor values at the appropriate locations in the distribution system. Proper capacitor placement can maintain voltage levels within permissible limits, thereby reducing voltage drops and power losses. The study uses a quantitative research method with a simulation study and numerical analysis approach [23], [24]. This research adopts a quantitative and simulation-based approach to analyze and optimize power flow calculations in a 20 kV distribution system FDLF method. FDLF is selected for its capability to reduce computational complexity while maintaining acceptable levels of accuracy in load flow analysis [25], [26].

2.1. System modeling

The first phase involves constructing a mathematical representation of the 20 kV distribution network. Unlike high-voltage transmission, 20 kV systems require precise modeling of line impedances and load characteristics. Bus admittance matrix (Y_{bus}), this matrix represents the nodal topology of the network.

$$Y_{ij} = G_{ij} + j\, B_{ij} \tag{1}$$

The technical role defines the relationship between current and voltage at every node. In a 20 kV system, Y_{bus} is the fundamental framework used to calculate how power flows through various feeders and branches. Load representation means that the loads at the distribution level are modeled as constant power sinks ($P - Q$ loads).

$$S_i = P_i + j\, Q_i \tag{2}$$

The technical role defines the boundary conditions for the power flow equations, representing the real and reactive power demand at each distribution transformer.

2.2. Implementation of FDLF

The FDLF algorithm is implemented to solve the non-linear power flow equations by exploiting the physical decoupling between real power/angle and reactive power/voltage.

– Active power sub-problem

The technical role means that this equation solves for phase angle corrections ($\Delta\theta$). The matrix B' is a simplified version of the Jacobian, where resistance R is often neglected relative to reactance X to allow for faster, non-iterative updates of the matrix.

$$\left[\frac{\Delta Q}{V}\right] = \left[B^{"}\right][\Delta\theta] \tag{3}$$

– Reactive power sub-problem

The technical role means this solves for voltage magnitude corrections (ΔV). B'' represents the sensitivity of voltage to reactive power changes. By solving these two equations separately, the computational speed is increased by up to 5 times compared to the standard Newton-Raphson method.

$$\left[\frac{\Delta Q}{V}\right] = \left[B^{"}\right][\Delta V] \tag{4}$$

2.3. Rationalization of capacitor bank sizing

To optimize the system, capacitor banks are sized not by trial and error, but through technical rationalization based on the reactive power deficit.

– Reactive power injection formula

The technical role means this determines the exact megavolt-ampere reactive (MVAR) required to improve the power factor (PF) from an inefficient state (e.g., 0.8) to the target state (e.g., 0.95). It ensures that the capacitor Vbank is not oversized, which could cause overvoltage during light-load conditions.

$$Q_{cap} = \left(tan\,\emptyset_{initial} - tan\emptyset_{target}\right) \tag{5}$$

– Voltage sensitivity factor (VSF)

The technical role means this derivative identifies the most sensitive buses in the 20 kV system. Capacitors are 2.

$$VSF = \frac{\partial V_i}{\partial Q_i} \tag{6}$$

2.4. Simulation workflow

The optimization process follows a rigorous sequential workflow to ensure the validity of the results: (i) data acquisition; (ii) base case simulation; (iii) optimal sizing and placement; (iv) iterative optimization: re-running the FDLF simulation with the integrated capacitor models; (v) convergence checkand; and (vi) performance evaluation.

2.5. Power flow analysis using the fast-decouple method

FDLF method is commonly used in power system studies to determine the steady-state behavior of an electrical network. Load flow analysis primarily aims to calculate the voltage magnitudes and phase angles at each bus, along with the active and reactive power flows throughout the system [27], [28]. This data is essential to guarantee dependable, effective, and safe functioning of the power system. FDLF is an easier and faster adaptation of the Newton-Raphson technique. It aims to minimize computational workload and memory consumption, particularly in extensive power systems.

3. RESULTS AND DISCUSSION

3.1. Calculation of capacitor bank requirements

The use of capacitor banks can be calculated:

$$\begin{aligned} Q_1 &= \sqrt{S^2 - P^2} \\ &= \sqrt{6689.332^2 - 5685.932^2} \\ &= 3523.824\ kVAR \end{aligned}$$

$$Q_2 = P \times Tan\varphi_2$$
$$= 5685.932 \times Tan\varphi_2(Cos^{-1}0.95)$$
$$= 5685.932 \times 0.32$$
$$= 1819.498\ kVAR$$

The required capacitor bank size for the Flamboyan Feeder is:

$$Cos_1 = 0.85$$
$$Cos_1{}^{-1} = 31.8°$$
$$Cos_2 = 0.95$$
$$Cos_2{}^{-1} = 18.2°$$

The capacitor bank size required for the Flamboyan Feeder has a voltage of 20.6 kV and a load current of 187.48 Amperes.

$$P = \sqrt{3} \times 20600 \times 187.48 \times 0.85$$
$$= 5689932.743 \text{ W}$$
$$= 5689.932 \text{ kW}$$

Hence,

$$Qc = tan\ \varphi_{initial} - tan\ \varphi_{target}$$
$$= P\ (tan\ 31.8 - tan\ 13.2)$$
$$= 5689.932\ (0.62 - 0.33)$$
$$= 5689.932 \times 0.92$$
$$= 1648\ kVAR$$

Therefore, the required capacitor reactive power (Qc) is:

$$K = \frac{kVAr_{Capacitor}}{kVAr_{Total}}$$
$$= \frac{1648.92}{1819.498}$$
$$K = 0.9$$

$$kVAr = 0.92 \times kVAr_{Capacitor}$$
$$= 0.92 \times 1648$$
$$= 1494 \text{ kVAr}$$

Based on Table 1, it can be seen that capacitor 1 has a value of 3524 kVAR and capacitor 2 has a value of 1819 kVAR. As for the required capacitor reactive power 1494 kVAR while the active power obtained is 5689 kW

Table 1. Comparison of voltage and losses before and after the installation of 2×900 kVAr capacitor banks on Feeder 7

No	System status	Lowest acceptable voltage		Total losses	
		kV	Location	Active power loss	Reactive power loss
1	Existing conditions	0.887 Pu (17.74)	Bus 27	0.531	1.019
		0.882 Pu (17.64)	Bus 52		
2	After installing the capacitor bank	0.958 Pu (19.16)	Bus 27	0.375	0.689
		0.951 Pu (19.02)	Bus 52		

So that the voltage received at transformer BK 052 is obtained:

$$V_r = V_{GI} - \Delta V_{GI \rightarrow BK052}$$
$$= 20600 - 398.92$$
$$= 20201 \text{ Volt}$$

3.2. Determination of optimum capacitor placement

The total required reactive power Qc of the capacitor for the line is 1949 kVAr. If one capacitor unit has a capacity of 900 kVAr, then the number of capacitor units required is:

$N = \frac{1,494.333}{900}$
$N = 1.6$
$N = 2$ capacitor unit

Therefore, the capacitors to be installed to improve voltage drop and power factor are two units, each with a capacity of 900 kVAr. The optimum placement of the capacitors can be determined based on the total line length of 181.5 km. Given the presence of two long branches, the author selects the branch line lengths as the following.

– Capacitor 1 is placed on the first branch with a total line length of 92 km.

$X_1 = \left[1 - \frac{2\times1-1}{2\times2} 0.45\right] \times 92$
$= 0.88 \times 92$
$X_1 = 80$ kM (at transformer BG 236)

– Capacitor 2 is placed on the second branch with a total line length of 124 km.

$X_2 = \left[1 - \frac{2\times2-1}{2\times2} 0.45\right] \times 124$
$X_2 = 0.66 \times 124$
$X_2 = 81.84$ (at transformer BG 117)

The voltage calculation after installing a 2400 kVAr capacitor bank on the feeder is as:

$I_C = \frac{P}{\sqrt{3}.V.cos\theta}$
$I_{GI\to BK053} = \frac{5,685.932}{\sqrt{3}\times 20.6\times 0.95}$
$= 167.75$ Ampere

Therefore,

$\Delta V_{GI\to B052} = \sqrt{3}.I.Z_{GI\to BK052}$
$= \sqrt{3} \times 167.75 \times 1.373$
$= 398.92$ Volt

3.3. Calculating basic impedance

To simplify the calculation of all impedances, each load is converted into one. Here, the author uses:

$MVA_{base} = 100$ MVA and $kVA_{base} = 20$ Kv
$Z_{base} = \frac{kV^2}{MVA_{base}}$
$Z_{base} = \frac{(20\times10^3)^2}{100\times10^6}$

Calculating Bus 1 – Bus 2, the line uses a 240 mm^2 AAAC conductor with an impedance of (0.134 + j 0.314) over a length of 24 km. Therefore, the line impedance is $3.216 + j\ 7.584$ Ohm/km. So, the impedance of channel Bus 1 – Bus 2:

$Z_{bus\ 2} = \frac{Z_{bus\ 2}}{Z_{base}}$
$Z = \frac{3.216 + j\ 7.584}{4}$
$Z = 0.804 + j\ 1.896$ pu

3.4. The channel impedance from Bus 1 to Bus 2 is pu

Using the same equation, we can calculate Bus 2 – Bus 3 using AAAC 150 mm² conductor with an impedance of $(0.216 + j\ 0.3305)$ ohms over a length of 3 km. Thus, the line impedance is $0.648 + j\ 0.9915$ ohms/km.

$$Z_{bus\ 2} = \frac{Z_{bus\ 2}}{Z_{base}}$$
$$Z = \frac{0.648 + j\ 0.992}{4}$$
$$Z = 0.162 + j\ 0.248 \text{ pu}$$

3.5. Analysis results using the fast decouple method for existing conditions before and after installation of the 2×900 kVAr capacitor bank

Based on Table 1, power loss savings/reductions are obtained. For active power is 0.531–0.375 MW = 0.156 MW or 156 kW while for reactive power is 1.019–0.689 MVAr = 0.330 MVAr or 330 kVAr. From the existing conditions and after the installation of the capacitor bank, the graph shown in Figure 3 is obtained. From Figure 3, it can be seen that the voltage drop from the existing condition at Bus 27 was 17.740 kV and at Bus 53 was 17.640 kV. After installing capacitors with a capacity of 2×900 kVAr, the voltage at Bus 27 became 19.160 kV and at Bus 52 became 19.020 kV.

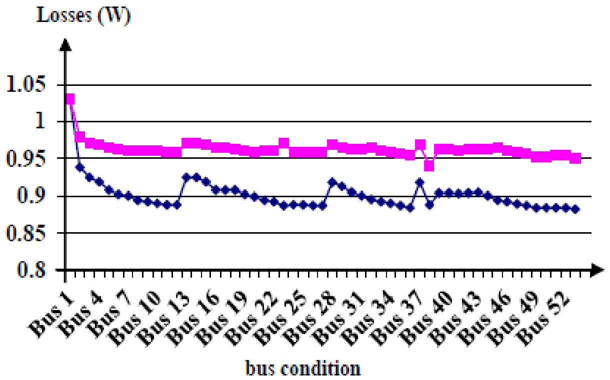

Figure 3. Capacitor bank installation chart

Compared to Newton-Raphson (NR), while NR is highly accurate, it is computationally heavy because it recalculates complex matrices in every step. FDLF is significantly faster because it simplifies these calculations, making it more efficient for 20 kV systems that require quick processing. Compared to Gauss-Seidel (GS), GS is mathematically simple but often fails or takes too long to converge in large networks. FDLF is much more stable and reliable, ensuring faster results even when dealing with many nodes in a 20 kV distribution grid. Conclusion for 20 kV Systems (in 20 kV networks), FDLF serves as the ideal middle ground: it is faster than NR and more stable than GS.

4. CONCLUSION

The accuracy and efficiency of the FDLF method proves to be highly capable of providing accurate and efficient results in analyzing the voltage profile of a 20 kV distribution system. It allows for rapid identification of critical nodes within the network with minimal computational overhead. Identification of voltage deficiencies shows that simulation results under existing conditions revealed significant voltage drops that compromised system standards. Specifically, the voltage at Bus 27 was recorded at 17.740 kV, while Bus 53 experienced a critical drop to 7.640 kV, indicating a severe deviation from the nominal operating voltage. The impact of strategic intervention reveals that the installation of capacitor banks with a total capacity of 2×900 kVAr significantly improved the system's power quality. Following this intervention, the voltage at Bus 27 increased to 19.160 kV, and the voltage at Bus 52 rose to 19.020 kV, effectively stabilizing the network and enhanced system reliability.

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The author indicates that there was no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Abrar Tanjung	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	
David Setiawan		✓				✓		✓	✓	✓	✓	✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The author reports no conflicts of interest related to this work.

DATA AVAILABILITY

Data availability is not applicable to this study because it did not involve the generation or analysis of new data.

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