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Multi-objective optimal reactive power planning using particle swarm optimization

Wielokryterialne optymalne planowanie mocy biernej przy użyciu optymalizacji roju cząstek

***Abstract**. The enhanced multi-objective deterministic reactive power planning power system presented in this study takes wind power production and load demand uncertainties into account. Reactive power planning comprises of all the planning steps required to improve electricity networks' stability and voltage profile. This study utilizes a Multi-Objective+Particle Swarm Optimization technique to get the most optimum Renewable Power Production (RPP), while considering the inherent uncertainty related to renewable sources. Attaining goals of preserving the high voltage profile while concurrently decreasing the costs linked to the implementation of VAr results in a mutually advantageous conclusion. The test bus system IEEE 30 is utilised to assess the suggested method's efficacy.*

Streszczenie: Ulepszony wielocelowy deterministyczny system planowania mocy biernej przedstawiony w tym badaniu uwzględnia niepewność produkcji energii wiatrowej i zapotrzebowania na moc. Planowanie mocy biernej obejmuje wszystkie kroki planowania wymagane do poprawy stabilności sieci elektroenergetycznych i profilu napięcia. W tym badaniu wykorzystano technikę optymalizacji wielocelowej + roju cząstek, aby uzyskać najbardziej optymalną produkcję energii odnawialnej (RPP), biorąc pod uwagę nieodłączną niepewność związaną ze źródłami odnawialnymi. Osiągnięcie celów zachowania profilu wysokiego napięcia przy jednoczesnym zmniejszeniu kosztów związanych z wdrożeniem VAr prowadzi do wzajemnie korzystnego wniosku. System magistrali testowej IEEE 30 jest wykorzystywany do oceny skuteczności sugerowanej metody.

Keywords: VAR, s compensator; multi-objective optimization; wind and load uncertainty; wind plant
Słowa kluczowe: VAR, kompensator s; optymalizacja wielokryterialna; niepewność wiatru i obciążenia; elektrownia wiatrowa

Introduction

Reactive power planning is the most difficult and complex task in power systems because of the numerous variables, constraints, and optimization strategjes involved [1]. It has to do with the best possible size and distribution of VAR sources inside power systems to meet prearranged goals, such figuring out the best possible distribution system and cutting down on operating expenses [2,3]. In the presence of VAR support conditions, the primary goal of RPP is to achieve viable operation with a respectable voltage profile. Different goal functions may be developed for the RPP issue in accordance with the power systems VAR planning paradigm.

The study of deterministic decision-making processes in RPP studies focuses on the uncertainty of load demand or source. This field of research is well-developed. The deterministic multi-objective RPP in power systems, which takes into account the simultaneous unpredictability of wind plants and loads, has received enough attention. In [4], a novel approach to dynamic VAR planning is introduced with the aim of improving transient and short-term voltage stability. The analysis examines the impact of capacitor/facts devices in Reactive power planning. However, an attempt has been made to provide a deterministic foundation for the problem in both instances. Authors [8], present a multi-objective Reactive power planning that primarily focuses on voltage stability. Nevertheless, it is constructed using a deterministic approach. Reference [9] presents a multi-objective approach for solving the resource-constrained project scheduling problem that includes wind energy. Numerous goals are taken into account in this study, including power losses, the cost of purchasing reactive power, and the capacity of the system to handle the load. Evolutionary algorithm enhance the process of optimization, [10], a Genetic Algorithm (GA) is used to solve the reactive power planning problem in [11], focusing on coordinating the control of reactive power in systems that include wind plants and capacitor/FACTS devices. The study aims to optimize the system's load ability factor by determining the optimal placement of wind plants and capacitor/FACTS devices.

Wind power uncertainty and modeling

The energy generated by a wind power plant is subject to fluctuations due to changes in wind speed, rendering it unpredictable. The wind power facility's erratic production may be attributed to either the system operator or a third party, among other potential causes. Previously, there was a penalty for the third-party proprietor who failed to respect the authority they had promised. As the wind plant are now under the jurisdiction of the system operators, there are now no repercussions for the wind plant if they provide less power than first pledged. If the amount of wind power generated is exaggerated, more energy is procured from other sources to meet the demand for power. According to references [12] the penalty is applied to invoices that prove their durability and economic importance. In addition, if the power is inaccurately computed, farms are compelled to decrease their power output, leading to an inappropriate use of wind energy and ultimately have a detrimental impact on the environment. This has detrimental effects not just on the economy but also on the operational longevity [13, 14]. The Weibull distribution offers statistical support for the varying wind speeds [15]. Statistical validation of the changing wind speeds is provided by the Weibull distribution [13] as represented in eqn. 1. and Fig. 1.

$$f(v) = \frac{k}{c}\left[\frac{v}{c}\right]^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \tag{1}$$

Whereas v, k and c are speed of wind, shape and scale factor, respectively. The output power of the wind turbine strongly depends on the speed of wind and is represented in eqn. 2.

$$P_{wt} = \begin{cases} 0 & V_t < V_c \\ P_R \frac{V_t^2 - V_c^2}{V_R^2 - V_c^2} & V_c < V_t < V_R \\ P_R & V_R < V_t < V_F \\ 0 & V_F < V_t \end{cases} \tag{2}$$

The rated power of the turbine is indicated by its maximum power output, whereas the cut-in speed refers to the lowest speed required for the turbine to begin functioning. Conversely, the rated speed denotes the most efficient speed at which the turbine operates, while the cut-out speed signifies the highest speed at which the turbine ceases to function. The reactive power 0f Wind Turbine Generator System is determined by solving the induction generator model. Table 1 represents the Wind turbine characteristics & Fig. 2 represents Weibul Estimated Wind Power.

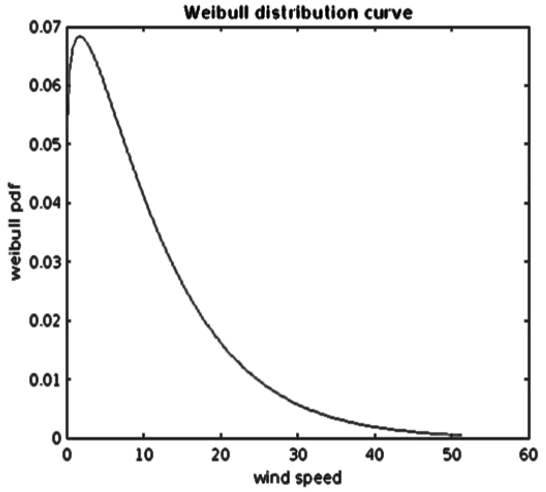

Fig. 1 Weibull Distribution Curve

Table 1: Wind turbine characteristics

Cut-in wind speed	3 m/s
Cut out wind speed	25 m/s
Max. wind speed	12 m/s
Wind power rating	40 MW

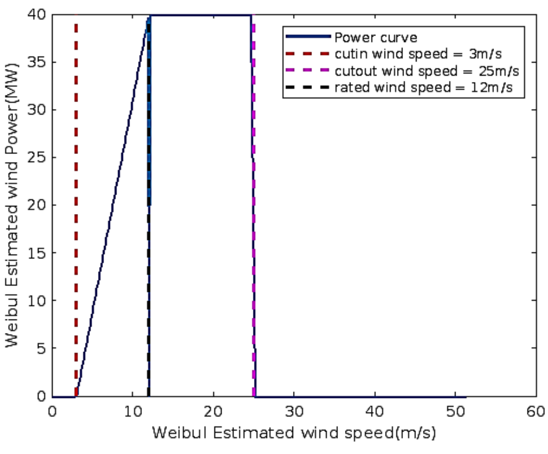

Fig. 2. Weibull distribution curve representing the hourly wind speed data, along with its Estimated wind power profile.

Problem Formulation

As was previously indicated, a large variety of Objective functions can be defined for reactive power planning (RPP) in power systems while taking into account all the constraints associated with the RPP problem, including the control and state variables. Therefore, all goals can be met, all limitations can be addressed, and the problem's viability can be guaranteed with a good formulation. Proper utilization of probabilistic variables in the problem formulation is essential since the problem's probabilistic character greatly influences how it is formulated.

Design of MO-optimization- problem

The multi-objective optimization function, which incorporates several objective functions considered in the problem, may be represented as in eqn. 3. subject to constraints.

$$\text{Minimize } \{fobj1, fobj2, fobj3\} = \{C_F, L_{max}, P_{Loss}\} \quad (3)$$

The dependent variable vector includes the power output of the active slack bus, the voltage magnitudes at the load buses (N), the reactive power injections from generators (Ngen), and the transmission line loadings (M), as specified in eqn. 4.

$$S = [P_{G1}, V_{L1} \ldots V_{LNgen}, Q_{G1} \ldots Q_{GN}, S_{L1} \ldots S_{LM}] \quad (4)$$

The control variables vector, denoted as u (eqn. 5), includes the active power output of the PV buses (excluding the slack bus), the terminal voltages of the generators, the tap settings of the transformers (N), and the settings of reactive power compensation devices (shunt-connected, Nc devices)

$$u = [P_{G2} \ldots P_{GNgen}, VG_1 .. V_{GNgen}, T1 .. T_N, Q_{C1} \ldots Q_{CNc}]^T \quad (5)$$

- **Variables**

Reactive Power Planning (RPP), like other power system optimization problems such as Optimal Power Flow (OPF), involves two types of variables: control variables and state variables. In a standard RPP scenario [12], control variables typically include the generator voltage magnitudes, transformer tap settings, and reactive power outputs of VAR sources.

- **Objective Functions**

The objectives covered by this study are to reduce the overall cost related to the VAR investment and enhance the voltage stability index. These goals lead to an overall decrease in total active electric power losses and an enhancement in voltage stability, as demonstrated by previous research [16,17].

Constraints

It is indisputable that restrictions play a crucial role in establishing a viable space for the issue and meeting optimality requirements in order to identify the best solutions. Because of this, one of the top concerns in the formulation of the issue is accurately expressing the limitations. The equality constraints for the RPP are assumed to be the power flow equations. The generators' reactive power production, buses' voltage, and their active power are all maintained within the permitted range by adhering to limits [18, 19].

Restrictions on equality

Equations for the power flow serve as equality constraints in Reactive power planning. To employ the energy generated by a plant powered by wind along with the uncertain character of the problem, the eqns. 6 and 7 represent constraints on active and reactive powers respectively.

$$P_{Gj} + P_{Wi} - P_{Di} = V_{i,j} \sum_{j=1}^{Nb} V_{j,s} Y_{ij} \cos(\theta_{ij} - \theta_{j,s} - \gamma_{ij}) \quad (6)$$

$$Q_{Gj} + Q_{Wi} - Q_{Di} = V_{i,j} \sum_{j=1}^{Nb} V_{j,s} Y_{ij} \cos(\theta_{ij} - \theta_{j,s} - \gamma_{ij}) \quad (7)$$

Restrictions on inequality

The generators should generate power within the specified range, and the voltage of the buses should also be within the permissible range.

$P_{gj(minimum)} \leq Pgj \leq P_{gj(maximum)}$ j ∈ Ngenerator

$Q_{gj(minimum)} \leq Qgj \leq Q_{Gj(maximum)}$ j ∈ Ngenerator

$Vgj_{(minimum)} \leq Vgj \leq V_{gj(maximum)}$ j ∈ Ngenerator

The power passed on via the branches is restricted to its greatest magnitude in a specific manner:

$|S| \leq S_{li(maximum)}$, i ∈ Nline (8)

The equation demonstrated below explains the restrictions on tapping levels via tap changers:

$T_{Gj(minimum)} \leq TGj \leq T_{Gj(maxmum)}$, j∈ NT (9)

Limitations on shunt VAR compensator

$Q_{Gj(minimum)} \leq QCi \leq Q_{Gj(maximum)}$, j ∈ NC (10)

The limitations for the reactive power compensation steps are as follows:

$I_{Cj(minimum)} \leq ICj \leq I_{Cj(maximum)}$

The wind plant's reactive and active energy outputs will be assessed within established limits.

$0 \leq P_{Wi} \leq \delta_{Wi;s} \leq Pr \times Wi$

System description

The effectiveness of the suggested technique is assessed by using a modified Institute of Electrical and Electronics Engineers 30-bus test system with an energy rating of 100 MVA as shown in Fig. 3.The usual Newton-Raphson technique is used to calculate the power flow. An alteration implemented in the testing system is the incorporation of a 40 MW wind energy generation system that is linked to bus number 20. Four more tapped transformers have been put on the power line which links buses 6-9,6-10, 4–12, and 27–28.

Additionally, reactive power sources have been included into buses 24, 25, 26, 28, 29, and 30. Table 1 displays the values for cut in, cut out, rated wind speed, and rated wind power, together with references to sources [13,14]. Figure 2 displays the forecasted wind profile in correlation with wind velocity. When the wind speed reaches 12 m/s, the wind turbine will start producing 40 MW of wind energy. However, The turbine will automatically shut down for wind speed higher than 25 m/s. An additional 40 MW of electricity is integrated into bus 20 [20,21]. Six of the 30 buses in the IEEE 30-bus system are devoted to generators. The slack bus is comprised of PV buses 2, 5, 8, 11, and 13, while the other 24 buses are PQ buses.

The 41 branches of the network are made up of six capacitor banks and four transformers. Transformers that change the load on tap are applied to four branches in total: 6-9, 6-10, 4-12, and 28-27. The tap ratios fall between [0.9 and 1]. The active/reactive power flow at each bus is determined using Newton Raphson load flow analysis. It has been observed that by adding wind power at bus 20 enhances the voltage profile at 100% wind power. [22,23]

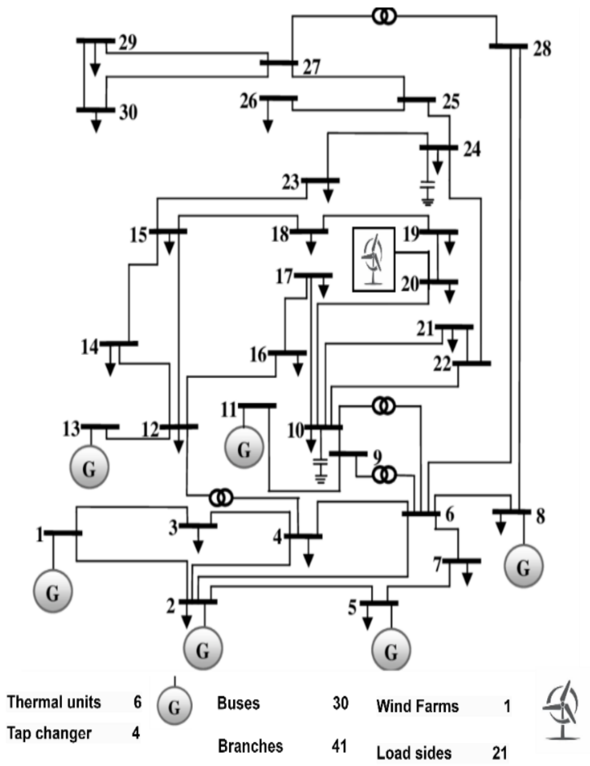

Fig. 3. IEEE 30 bus system with Wind plant at bus 20.

Result and discussion

In this work, six sensitivity buses are selected from the sensitivity analysis method at which VARs are installed. PSO is used to optimize the values of control variables (Final optimized values are given in Table 2. Using these values, the value of three objective functions for 4,5 & 6 VARs are given in Table 3.

Table 2: Optimized values of the control variables in one-year Reactive power planning

		PSO
Tap Ratios (p.u.)	t_{6-9}	0.9
	t_{6-10}	1.1
	t_{6-12}	0.9
	t_{27-28}	0.9
VAR compensators (MVAR)	*var-24*	0
	var-25	0
	var-26	0
	var-28	32.54
	var-29	0
	var-30	4.69

Table 3: Effect of the number of VARs in the Reactive power planning

Number of VARs	f_1(Power loss)	f_2 (Cost of VAR Device)	f_3(L-index)
6	9.358	558544.213	0.983
5	10.08	537134.02	0.972
4	11.5978	521518.377	0.9734

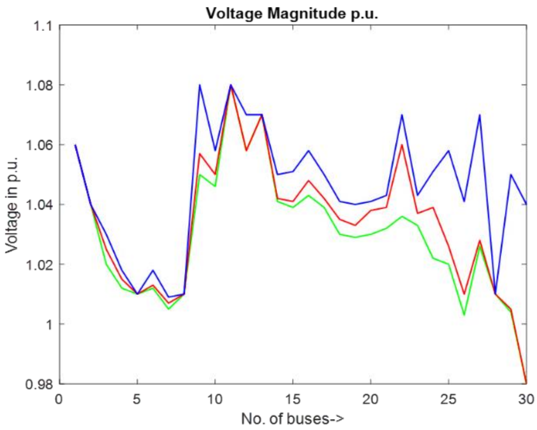

Fig. 4. Volage Profile (green: Normal case, red: with wind, blue: proposed)

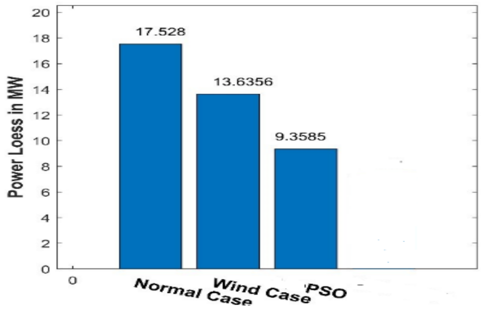

Fig. 5. Power loss comparison for the deterministic RPP

Conclusion and future scope

The proposed methodology has resulted in better voltage profile (as shown in Fig. 4 and reduced power losses (reduction from 17.528 MW to 9.3585 MW, i.e., 46% overall improvement) as shown in Fig. 5. Proposed optimized methodology using particle swarm optimization also helps in reducing the overall cost. In the future, we shall investigate the effects of contemporary FACT Devices together with RPP in extensive IEEE Standard bus systems like IEEE-69, IEEE-114, etc.

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