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Reactive Power Dispatch Algorithm for a Reduction in Power Losses in Offshore Wind Farms

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Abstract: This paper presents a groundbreaking power distribution technique that focuses on the loss rate of individual wind turbines. Distinct from conventional methods, our strategy prioritizes seamless integration and adaptability within wind farm management systems. By evaluating power losses in specific branches of a wind farm, our approach enhances overall performance by strategically allocating reactive power to reduce cumulative losses. When compared to traditional uniform distribution and Particle Swarm Optimization (PSO) methods, our innovative approach stands out for its superior efficiency and adaptability. Comprehensive simulations underline the strengths and weaknesses of prevailing methods and underscore the superior efficacy of our proposed technique.

Keywords: wind farm; active power loss; reactive power; reactive power dispatch; loss minimization; reactive power control

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1. Introduction

In recent years, the global energy landscape has undergone a significant transformation. The shift from conventional fossil fuels to renewable energy sources has become a central theme in discussions about sustainable development and environmental conservation.

With the growing emphasis on clean energy, the installed capacity of offshore wind power has been increasing faster than ever. Wind energy is a form of renewable energy with mature technology that has developed rapidly in recent decades. By the end of 2019, the total installed capacity of global offshore wind power reached 29.1 GW. A report on China's ability to power a huge growth in global offshore wind energy stated that the total installed capacity of global offshore wind power will reach over 234 GW by 2030. Compared with onshore wind power, offshore wind power has the advantages of high wind speed, regional climate stability, and no significant visual impact. Due to the high efficiency of offshore wind power, it is suitable for centralized development, which is an important development direction for wind power [1]. However, like all sources of energy, wind power comes with its own set of challenges.

Offshore wind farms operate in complex and variable conditions, exposed to strong winds, waves, and corrosion. This poses difficulties in ensuring farm stability, efficiency, and managing power transmission systems.

The significance of losses within offshore wind farms and transmission lines (TL) loss becomes increasingly evident as wind farms expand in capacity. This expansion naturally extends the internal network, thereby escalating the potential for losses. Moreover, the systems in these farms often operate at relatively low voltages while handling high currents, a combination that further exacerbates the magnitude of these losses.

These losses are not to be confused with other types of losses, such as those within the Wind Turbine (WT) or losses occurring outside the Point of Common Coupling (PCC) in the national power grid during transmission to consumers. Although these are also forms of losses, the focus of this study is specifically on losses inside the offshore wind farm and

TL loss. These losses are crucial because they can lead to inefficient resource utilization and increased operational costs.

It is undisputed that the optimal reactive power dispatch (ORPD) problem is one of the key focus areas in power system research. The ORPD problem can be found in many real-world power system applications. For example, wind farms with large power-generation capacities are expected to provide a necessary reactive power support capability. Having been developed for more than two decades, many classical optimization methods have been proposed to solve the ORPD problem, such as sequential quadratic programming (SQP), linear programming (LP), non-linear programming6, and interior point methods (IPM). Despite the success in terms of the accuracy and robustness of classical methods on some specific problems, most of these methods have difficulty in dealing with the problems that have non-linear and discontinuous objectives [2–7].

Particle Swarm Optimization (PSO) has been a beacon in the realm of optimization algorithms. Its application spans various domains, including, but not limited to, wind farm management. The algorithm's strength lies in its ability to find an optimal solution in complex solution spaces efficiently. However, no algorithm is without its limitations. PSO, when not fine-tuned for specific tasks, can sometimes fall short of expectations. This is especially true in dynamic environments like wind farms, where variables change frequently and often unpredictably.

Our research was motivated by the limitations of both traditional methods and the PSO algorithm. We sought to develop a method that not only addresses the shortcomings of these techniques but also offers a more efficient and adaptable solution. The result is the novel power distribution technique presented in this paper. In the proposed method, reactive power is distributed among wind turbines based on the percentage of active power losses. This means that turbines with the least losses release more reactive power and vice versa. This approach takes into account the unique characteristics of each turbine, optimizing the overall performance of the wind farm. The proposed method addresses these variations by allocating reactive power in a manner that minimizes total losses. Turbines with the least active power losses are tasked with generating a higher amount of reactive power, ensuring a more efficient resource distribution.

The decision to compare our technique with the PSO algorithm was deliberate. Given the widespread application and recognition of PSO in the field, it offers a robust benchmark against which we can measure the effectiveness of our proposed method. Through rigorous simulations, we contrast our technique with both even distribution and PSO techniques. The results, as will be discussed in subsequent sections, are promising and underscore the potential of our method.

Specialized software, such as DigSILENT Power Factory 2023, enables a more accurate representation and analysis of complex electrical systems in offshore wind farms.

2. An Offshore Wind Farm and Its Loss Calculation

2.1. Offshore Wind Farm Configuration

For this article, a model of an offshore wind farm has been designed, which includes the following components:

Number of Wind Turbines: The wind farm consists of two branches with five turbines each. The model incorporates the installation of ten wind turbines with a capacity of 10 MW each. This results in a total power output of 100 MW, capable of generating a sufficient amount of electricity to meet the needs of a specific region or city.

Array Cables: Array cables connect wind turbines at a distance of 1 km from each other. The cable cross-section increases as the turbine gets closer to the substation, as it carries the combined power of all interconnected turbines.

Offshore Substation: To collect and transmit the generated electricity from the wind turbines, an offshore substation is utilized. The offshore substation is equipped with a step-up transformer, designed to elevate the voltage level from medium voltage to high voltage.

The offshore substation serves the purpose of gathering, converting, and transmitting the electricity from the wind turbines to the onshore substation.

Submarine Cable: A submarine cable is employed to transfer the electricity from the offshore substation to the onshore substation. This cable ensures efficient and safe transmission of electricity across the seabed over significant distances. The wind farm configuration is illustrated in Figure 1.

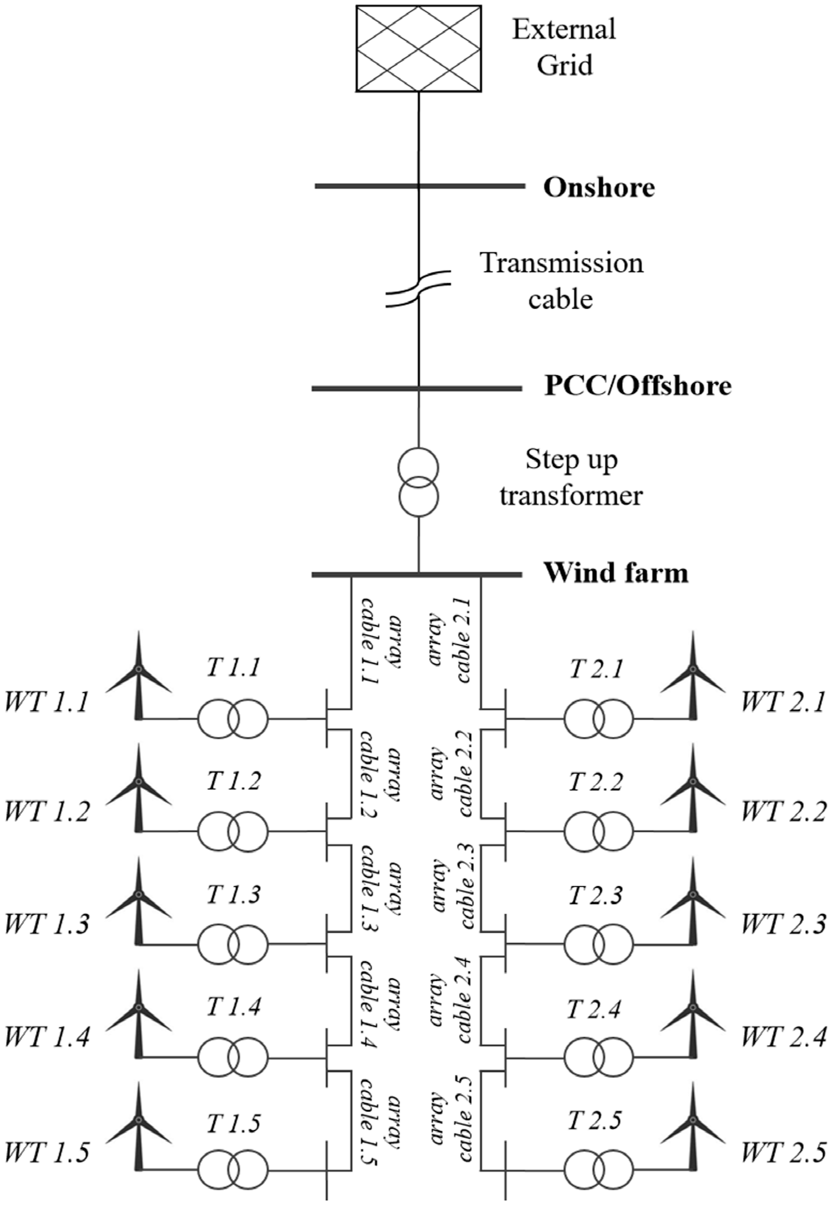


Figure 1. Wind farm configuration.

2.2. Calculation of Power Losses

The wind-generated electrical energy produced by wind turbines needs to be transmitted from the wind farm to the electricity consumption site. This transmission is facilitated by an electrical power transmission system, which includes cables, transformers, high-voltage transmission lines, and other components. During the process of electrical energy transmission, losses occur. These losses can be attributed to factors such as the resistance of the cables, losses in transformers, and losses in the power transmission lines [8–10].

The power loss element (cable, transformer, etc.) can be expressed as:

$$P_{loss} = I^2 R = \frac{P^2 + Q^2}{V^2} \cdot R \quad (1)$$

where P_{loss} is the power loss, which refers to the amount of power dissipated or lost within the wind turbine system. I is the current flowing through the element (cable, transformer, etc.). R is the electrical resistance of the element.

The equation states that the power loss is equal to three times the square of the current multiplied by the total electrical resistance. In the context of offshore wind farms, it is used to estimate the amount of power dissipation or losses occurring within the wind turbines.

As mentioned earlier, when calculating the power losses of a wind turbine up to the Point of Common Coupling (PoC), all components need to be considered [11–14].

$$P_{loss\_WT} = \sum_{k}^{n_{cab}} P_{loss_{cable(k)}} + \sum_{l}^{n_{tr}} P_{loss_{tr(l)}} + \sum_{m}^{n_{tran}} P_{loss_{transmission(m)}} \quad (2)$$

where n_{cab}, n_{tr}, n_{tran} are the upper limits of the summation, indicating the total number of elements to be summed up in each expression. k, l, m represent the index of each individual element, ranging from k, l, and m to n. $P_{loss.cable(k)}$, $P_{loss.cable(l)}$, $P_{loss.cable(m)}$ represent the power loss associated with each element indexed by k, l, and m.

The calculation of losses in the wind farm is shown in Equation (3).

$$P_{Total\_loss} = P_{loss\_WT_1} + P_{loss\_WT_2} + \cdots + P_{loss\_WT_n} \quad (3)$$

where P_{loss_WT} is power losses from wind turbine to PoC, n—number of wind turbine.

3. Loss Minimization Using Reactive Power Reference Dispatch

3.1. Convetional Method 1: Reactive Power Reference Dispatch Using 1/n Method

The strategy implemented by the wind farm controller involves dispatching the required reactive power among the operative generators in a proportional manner, taking into account their available reactive power capabilities.

To elaborate, the wind farm controller assesses the reactive power requirements of the system and determines the total amount of reactive power that needs to be generated. This total reactive power is then allocated proportionally among the wind turbines based on their individual reactive power capabilities.

Each wind turbine has a certain limit or capacity for generating reactive power, known as its available reactive power. The wind farm controller considers these capabilities and assigns a portion of the total reactive power requirement to each turbine, in proportion to its available reactive power.

By distributing the reactive power in this manner, the wind farm controller ensures that each wind turbine contributes its fair share based on its capacity. This approach helps to optimize the overall operation of the wind farm, maintain system stability, and comply with grid requirements. The wind farm controller continuously monitors the reactive power output of each turbine and adjusts the setpoints as necessary to maintain the desired reactive power dispatch. This control mechanism allows for dynamic adjustment and optimization of reactive power generation based on the real-time conditions and system demands [5,7,9].

Figure 2 shows the block diagram of wind farm reactive power controller.

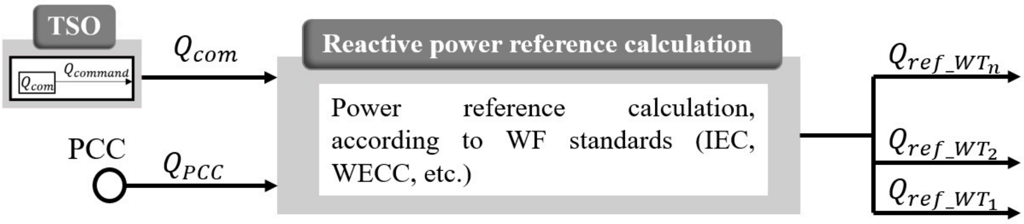


Figure 2. Wind farm reactive power controller block diagram.

3.2. Conventional Method 2: Reactive Power Reference Dispatch Using Particle Swarm Optimization

Particle Swarm Optimization was originally introduced by Eberhart and Kennedy according to swarm intelligence. In PSO, each d-dimensional particle xi is a possible solution. The particles collaborate as a population to reach a collective goal, usually to minimize a function f [15–20].

Firstly, in PSO, a group of particles is randomly generated as initialization. Then every particle is evaluated by calculating its fitness value using function f, thus the personal best position (pbest) and global best position (gbest) will be found. The velocity and position of each particle is updated according to pbest and gbest, as in the formula shows below [15–20]:

$$v_i{}^{k+1} = v_i{}^k + c_1 r_1 \left(pbest_i{}^k - x_i{}^k \right) + c_2 r_2 \left(gbest^k - x_i{}^k \right) \tag{4}$$

$$x_i{}^{k+1} = v_i{}^{k+1} + x_i{}^k \tag{5}$$

where $v_i{}^k$ and $x_i{}^k$ are the velocity and position of particle i at k-iteration, c_1 and c_2 are acceleration coefficients, r_1 and r_2 are random numbers between 0 and 1, $pbest_i{}^k$ is the personal best position of particle i at k-iteration, and $gbest^k$ is the global best position at k-iteration. After updating the velocity and position, a new generation of particles is generated. Repeat the work until the number of iterations reaches the set value or the change of gbest in N iterations is less than M (the value of N and M is set by users) [15–20].

The inertia takes a value for each iteration k; it is represented as follows:

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{iter_{total}} \cdot iter \tag{6}$$

where ω_{max} is initial weight, ω_{min} is the final weight, $iter_{total}$ is total iterations, $iter$ is current iteration.

The PSO method has inherent limitations affecting its effectiveness. One notable challenge is its potential for slow convergence, particularly if the algorithm's parameters are not optimally set. Moreover, the efficiency of PSO largely depends on the initial parameter choices, and unsuitable selections can hinder its performance.

Table 1 shows the development of PSO [15–20].

Table 1. Development of PSO.

Step	Name	Description
1	Establishment of Initial Particle Positions and Movements.	The starting positions and movements of each particle are established through the utilization of randomly generated state variables.
2	Calculation of Active Power Losses and Introduction of Penalties.	The active power losses at the positions of each particle are calculated by means of a power flow. If the constraints violate the allowable limits, a penalty for the losses is included.

Table 1. *Cont.*

Step	Name	Description
3	Determination of Local and Global Best Values.	Each search point has its known local position, referred to as pbest. The best-evaluated value, which is the sum of the loss and penalty, from all the pbest is then set as the global best, or gbest.
4	Computation of New Velocities and Search Positions.	The new search velocities and positions are calculated using (4)–(6).
5	Calculation of Power Losses and Evaluation.	The losses (Ploss) in the new search positions are calculated, and an evaluation is performed for each one.
6	Update of Evaluations and Best Values.	The evaluation of each particle is compared to its previous pbest and updated if it is better. The best of the pbest is then compared to gbest and updated if it is better. The updated gbest values are stored as potential solutions.
7	Termination or Return to Step 4.	When the maximum number of iterations determined is reached, and if the result meets the expectations, the search process will end. Otherwise, the process will return to step 4.
8	Computation of Reactive Power by Rotating Machines.	Using the results, the power flow calculation is performed to determine the reactive power dispatch by the rotating machines.

3.3. Proposed Method: Reactive Power Reference Dispatch based on Power Loss Percentages

The proposed method focuses on assessing power losses of turbines in a specific branch of a wind farm. If the farm consists of multiple branches, this algorithm specializes in calculating losses for the selected section, taking into account the total power losses of all turbines in that area.

The core concept of the proposed method revolves around distributing reactive power among wind turbines based on the percentage of active power losses. This approach takes into account the unique characteristics of each turbine, optimizing the overall performance of the wind farm.

The performance of a wind farm is influenced by the diverse characteristics of wind turbines and their operating conditions, which can result in varied active power losses. Our method directly addresses these disparities by strategically allocating reactive power to reduce overall losses.

Turbines with the least active power losses are tasked with generating a higher amount of reactive power, ensuring a more efficient resource distribution. The final step involves calculating the controlled power for each turbine. In this calculation, a formula is used that takes into account the initial reference power value from the wind farm controller for each turbine, multiplied by the overall loss coefficient and the number of turbines.

$$Q_{ref\_WT_1} = \frac{P_{loss\_WT_5}}{P_{Total_{loss}}} \cdot Q_{ref} \cdot n \tag{7}$$

$$Q_{ref\_WT_2} = \frac{P_{loss\_WT_4}}{P_{Total_{loss}}} \cdot Q_{ref} \cdot n \tag{8}$$

$$Q_{ref\_WT_3} = \frac{P_{loss\_WT_3}}{P_{Total_{loss}}} \cdot Q_{ref} \cdot n \tag{9}$$

$$Q_{ref\_WT_4} = \frac{P_{loss\_WT_2}}{P_{Total_{loss}}} \cdot Q_{ref} \cdot n \tag{10}$$

$$Q_{ref\_WT_5} = \frac{P_{loss\_WT_1}}{P_{Total_{loss}}} \cdot Q_{ref} \cdot n \tag{11}$$

where Q_{ref_WT} represents the reactive power allocated to the wind turbine. P_{loss_WT} is the active power loss for the wind turbine. $P_{Total_{loss}}$ signifies the total power loss for all wind turbines in the considered section of the wind farm. Q_{ref} is the initial reactive power value provided by the wind farm controller. n is the total number of wind turbines in the considered section of the wind farm.

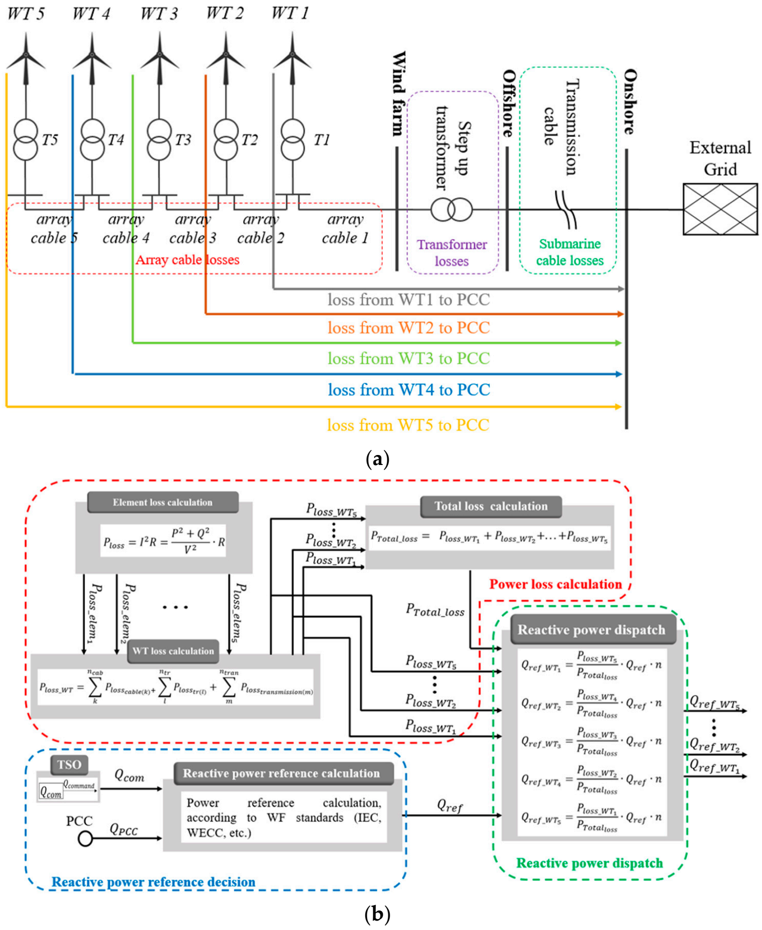
The core principle of our model is to allocate reactive power to wind turbines based on their respective active-power-loss percentages. By considering the distinct attributes of each turbine, this method aims to optimize the entire wind farm's performance.

Thus, the model provides a method for distributing reactive power among wind turbines in a way that minimizes total power losses and optimizes the operation of the wind farm.

A primary advantage of the proposed method is its adaptability. It can be tailored to work with various types of wind turbines and under different operational conditions. Additionally, the method can be seamlessly integrated into existing wind farm management systems.

Another significant benefit is the method's ability to strike an optimal balance between turbine performance and loss minimization. This can result in an enhanced overall efficiency of the wind farm and a reduction in operational costs.

In Figure 3, (a) presents a diagram of a wind farm with a single branch, while (b) depicts the proposed reactive power dispatch block diagram for the wind farm.



(**a**)

(**b**)

Figure 3. (**a**) Wind farm diagram with one branch; (**b**) Wind farm proposed reactive power dispatch block diagram.

The proposed method stands out from PSO by offering a swifter convergence to the optimal solution, thereby reducing computational time. It also exhibits a reduced sensitivity to the initial selection of parameters, diminishing the risk of suboptimal outcomes. Unlike PSO, which does not guarantee the identification of a global optimum, our method can provide more reliable assurances regarding solution quality. Moreover, while PSO might necessitate multiple runs to achieve the desired outcome, the proposed method is capable of attaining the target result with a single application.

4. Simulation

4.1. Implementation

The WPP model was implemented based on the standard IEC 61400-27 [21] for electrical simulation models of wind power generation. The wind power generation simulation model IEC 61400-27 is a fundamental wave RMS model that can be used to analyze the stability of large-scale power systems and grids of wind turbines and WPPs, and it was developed to simulate the dynamic characteristics of events of various power systems [22,23].

The WPP model implemented in this paper was composed of a WPP controller and a wind turbine model; the wind turbine was implemented as a type 4 model, a wind turbine type based on a full-scale converter [22,23].

The implemented offshore wind farm is shown in Figure 4.

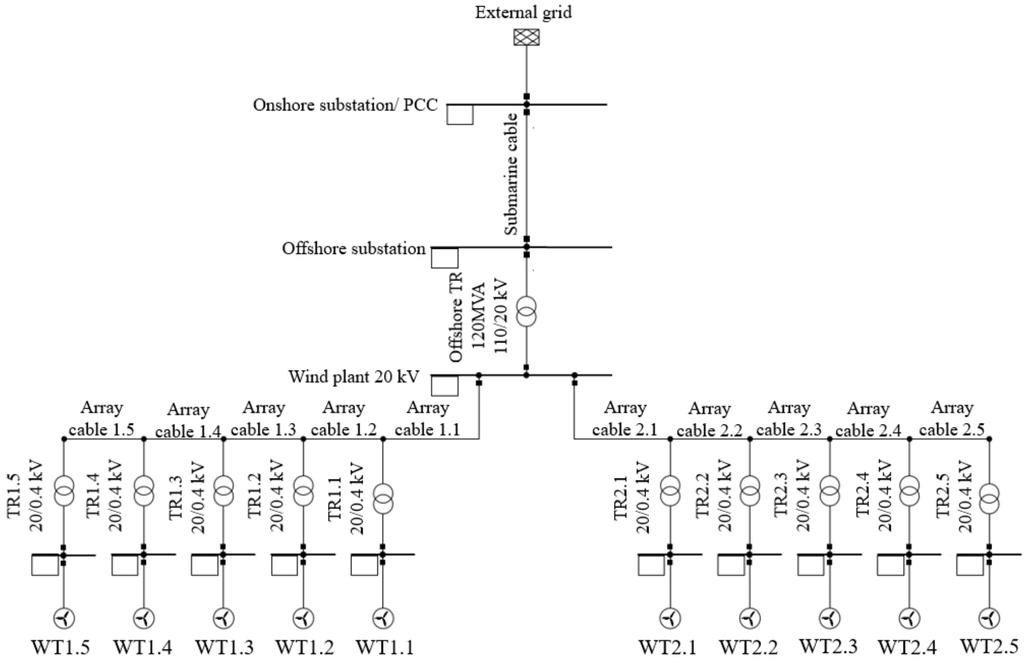


Figure 4. 100 MW wind farm implemented in DigSILENT Power Factory.

4.2. Method 1/n's Simulation Results

In Figure 5, the active and reactive power outputs from the turbines are delineated. When each wind turbine delivers a full active power of 10 MW, the wind farm's controller ensures a uniform distribution of reactive power among the turbines. Figure 6 presents the reactive power and associated losses at the PoC. For this simulation, the reactive power command was set at 0.2 pu, corresponding to 20 MVar. With a slight deviation, the reactive power is observed to be 19.52 MVar. Additionally, at an active power output of 100 MW, the losses are quantified at 2.59 MW. The wind farm controller reads the current values of active and reactive powers, as well as the voltage at the control point, and utilizes this information to maintain the desired reactive power setpoint. Using a PI controller, the wind farm controller adjusts the output reactive power to achieve the desired value.

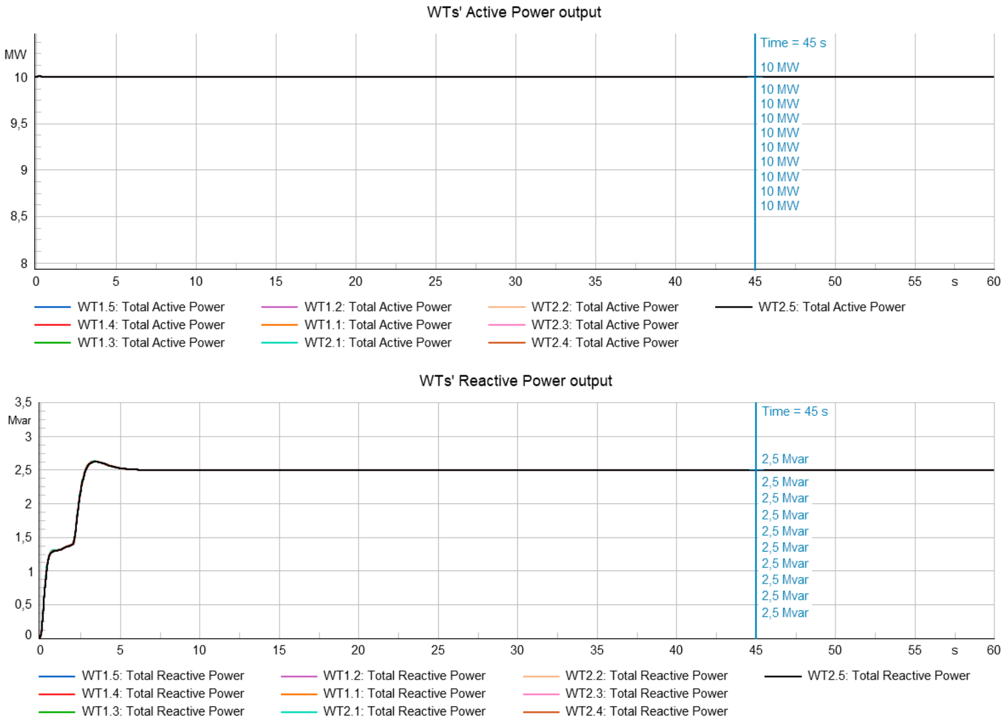


Figure 5. WTs' active and reactive powers output.

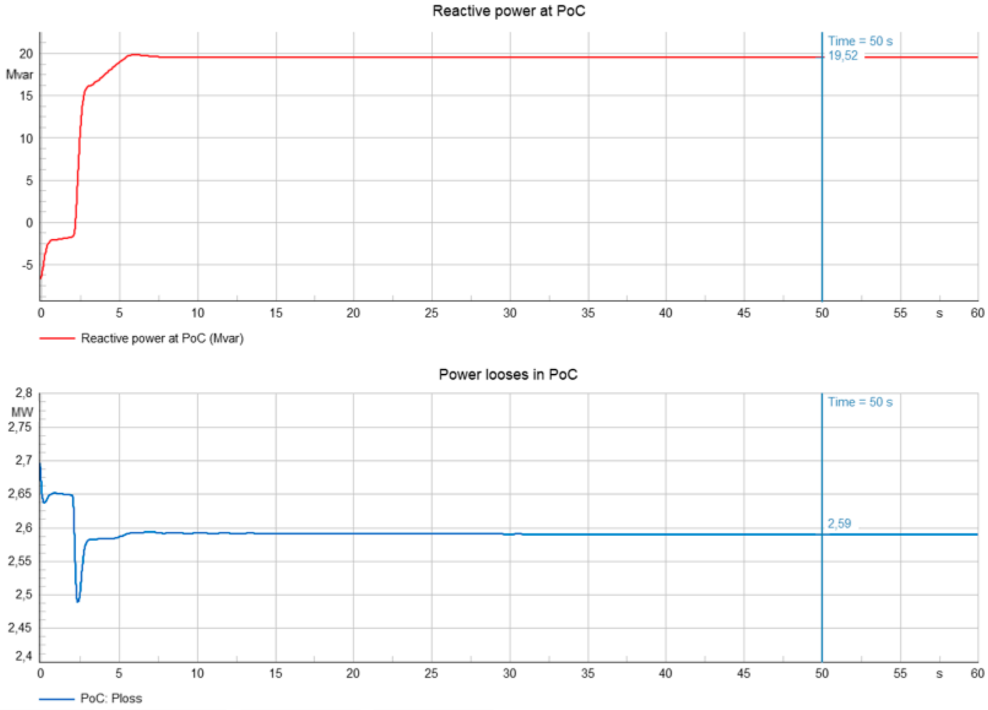


Figure 6. Reactive power and active power losses in PoC.

4.3. PSO's Simulation Results

Upon implementing the PSO method in the wind farm, Figure 7 reveals varying reactive power at the same active power level. The PSO algorithm, over the course of 1000 iterations, identifies the optimal reactive power for each turbine, taking into account the turbine's distance from the PoC, aiming to minimize the wind farm's active power losses.

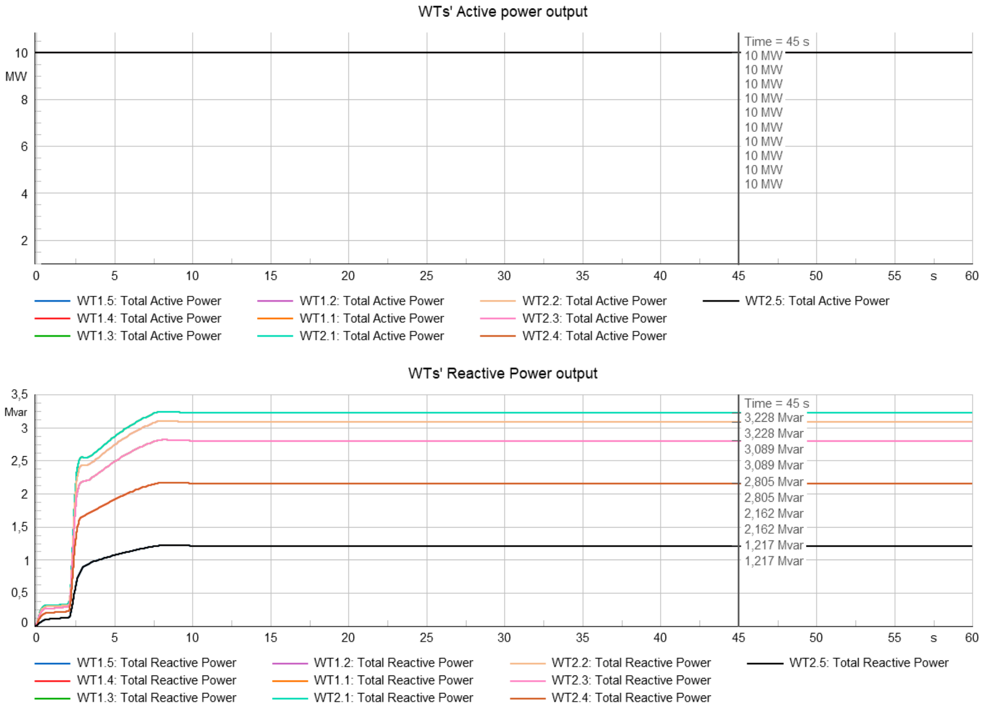


Figure 7. WTs' active and reactive powers output using PSO.

Furthermore, as shown in Figure 8, with the same reactive power command, there is a reduction compared to the results from the 1/n method. At a total power of 100 MW, the active power losses amount to 2.513 MW. In this scenario, a difference of 46 kW in active power losses is observed.

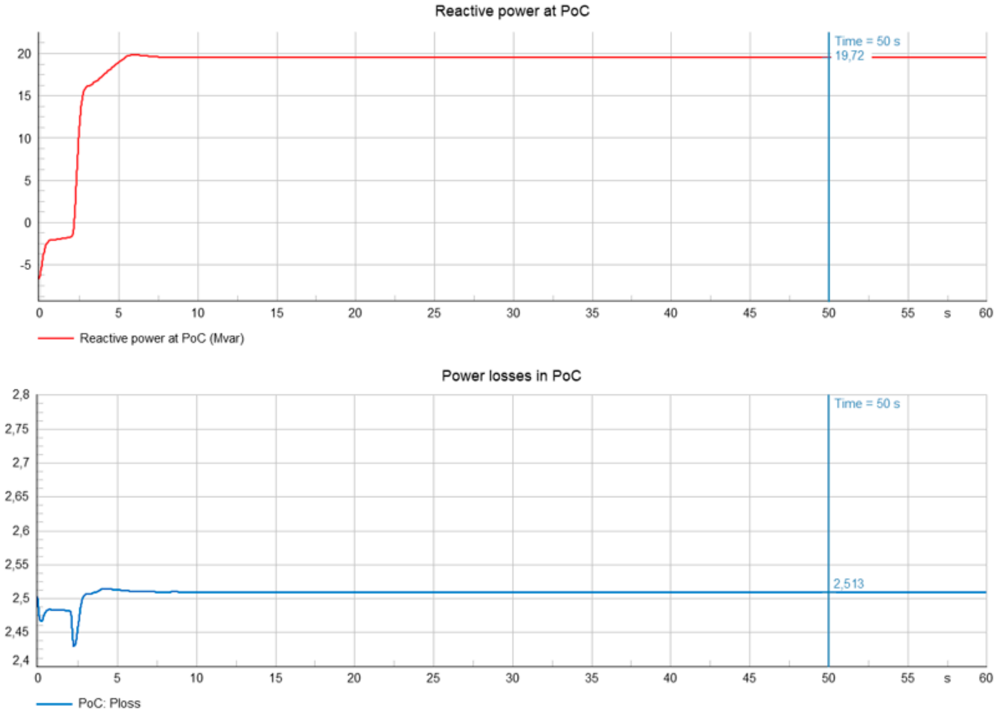


Figure 8. Reactive power and active power losses in PoC using PSO.

4.4. Proposed Method’s Simulation Results

In the proposed method, reactive power is distributed among wind turbines based on the percentage of active power losses. As can be seen in Figure 9, turbines with the least losses release more reactive power, and vice versa. As with the PSO method, at the same active power level, the turbines’ reactive power varies. However, in the current scenario, the difference between the turbines’ reactive powers is less than in the PSO method’s results.

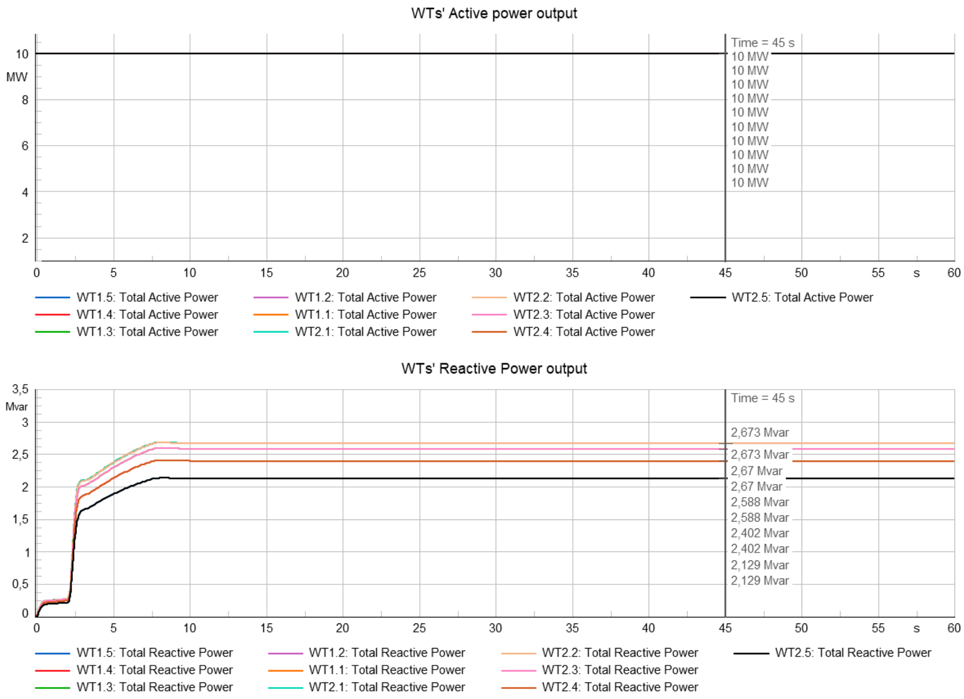


Figure 9. WTs’ active and reactive powers output using proposed method.

In Figure 10, the losses in the proposed method amount to 2.57 MW, which is less than the 1/n method, but greater than the PSO method.

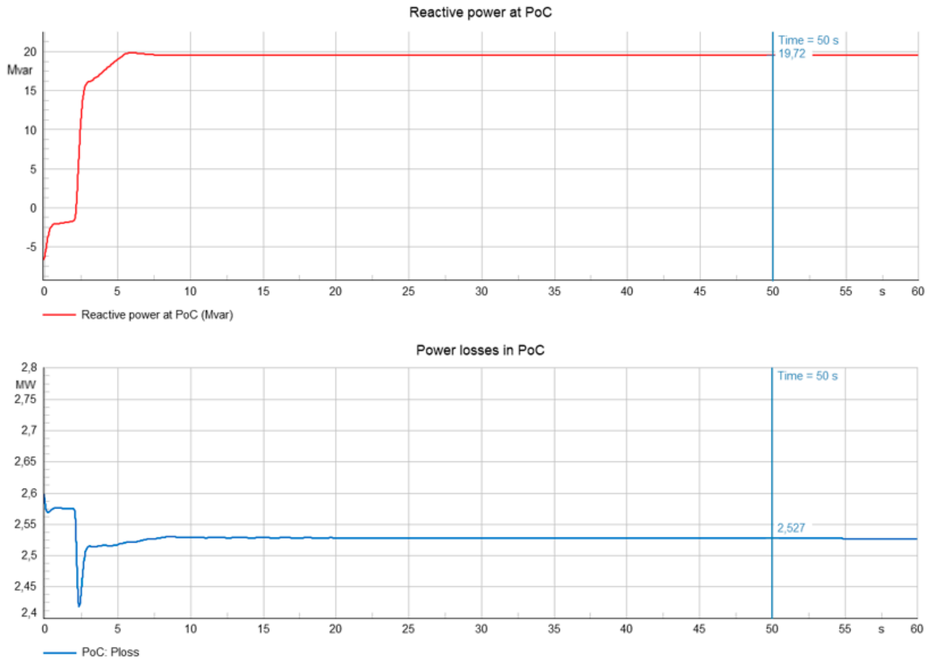


Figure 10. Reactive power and active power losses in PoC using proposed method.

4.5. Comparison between Algorithms

4.5.1. Comparison between Algorithms in 100 MW Output

For further analysis, a comparison of the results from three algorithms was conducted. Figure 11 displays the comparisons of reactive powers of wind turbines at a total wind farm power of 100 MW. As evident from the results, to minimize losses in both the proposed method and PSO, the reactive power of each turbine varies. The proposed method distributes reactive power based on percentage, whereas the PSO method seeks the optimal outcome, resulting in a larger difference between the turbines' reactive powers.

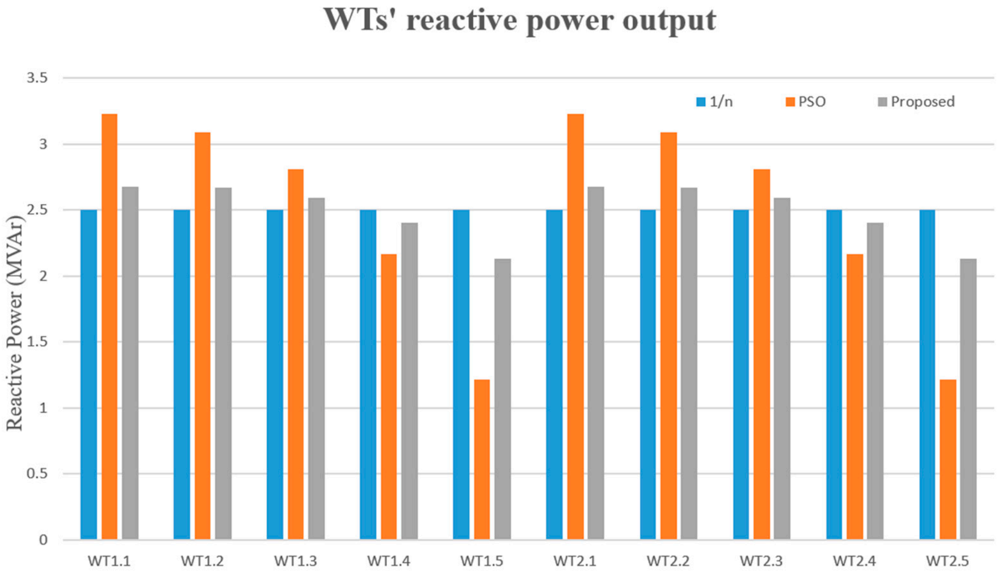


Figure 11. Comparison of WTs' reactive power outputs between dispatch algorithms in 100 MW output.

Figure 12 illustrates the difference in losses among the methods. According to the results shown in the figure, the highest losses are observed in the 1/n method. The proposed method exhibits reduced losses in the array cable, transformer, and submarine cable. There is a slight reduction in losses when using the PSO method compared to the proposed method.

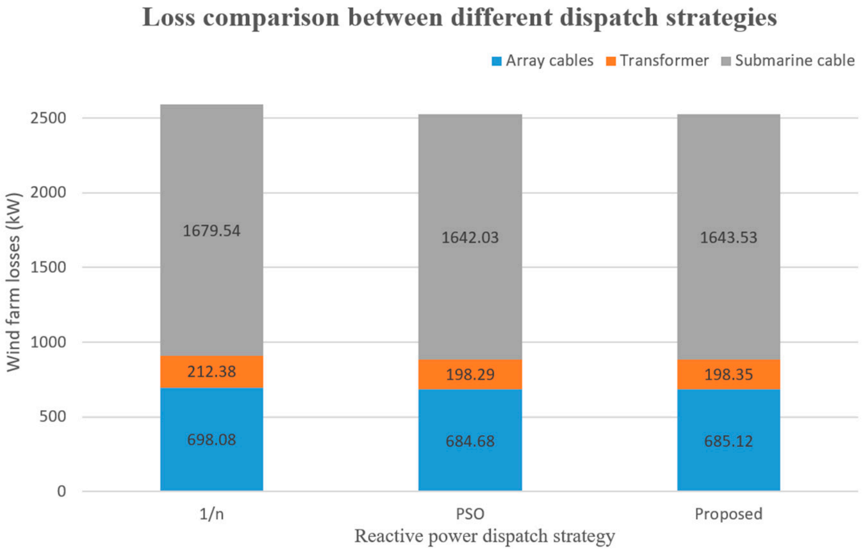


Figure 12. Comparison of power losses between dispatch algorithms in 100 MW output.

Figure 13 depicts the impact of reactive power on losses in the wind farm. According to the grid code, the reactive power in wind turbines should be within the range of −0.33 to +0.33 pu. The highest losses are observed at −0.33 pu, and there is also an increase in losses beyond 0.1 pu. In all instances, the PSO method demonstrates the best performance. However, the difference in results between the PSO and the proposed method is minimal, except in the case of a reactive power of 0.33 pu.

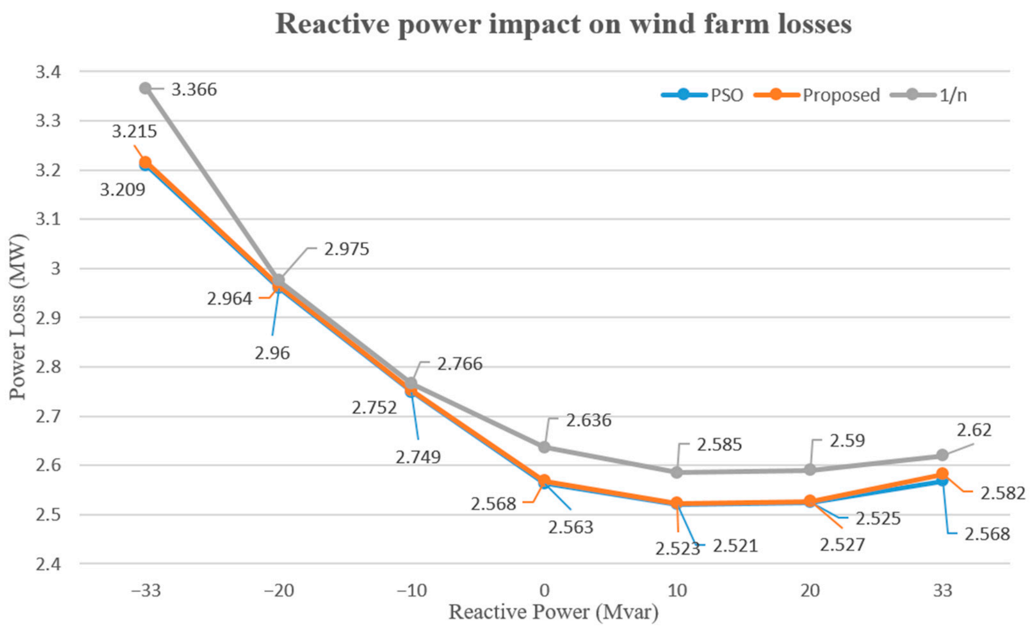


Figure 13. Reactive power impact on wind farm losses in 100 MW output.

4.5.2. Comparison between Algorithms in 20 MW Output

Further analysis was conducted at a wind farm active power generation level of 20 MW. In Figure 14, as with the case of a wind farm generating 100 MW of active power, it is evident that the difference in reactive power distributed among the wind turbines is higher in the PSO method compared to the proposed method.

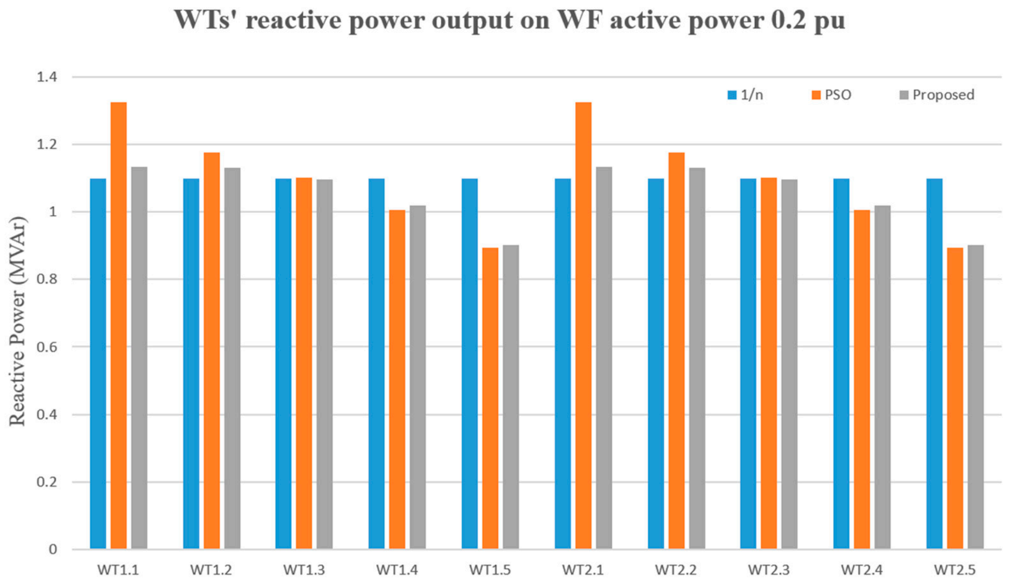


Figure 14. Comparison of WTs' reactive power outputs between dispatch algorithms in 20 MW output.

This difference has an impact on the losses experienced by the wind farm. As shown in Figure 15, the losses in the proposed method and PSO are lower compared to the 1/n method. In Figure 16, the impact of reactive power on wind farm losses is illustrated, particularly focusing on a 20 MW output. While the losses in the proposed method are slightly higher than those in PSO, the observed differences in losses are minimal, indicating a consistent trend across various levels of reactive power, from −0.33 pu to 0.33 pu. This consistency underscores the effectiveness of our proposed method. Given the known limitations of PSO, our method emerges as a more reliable and promising approach to manage reactive power in wind farms.

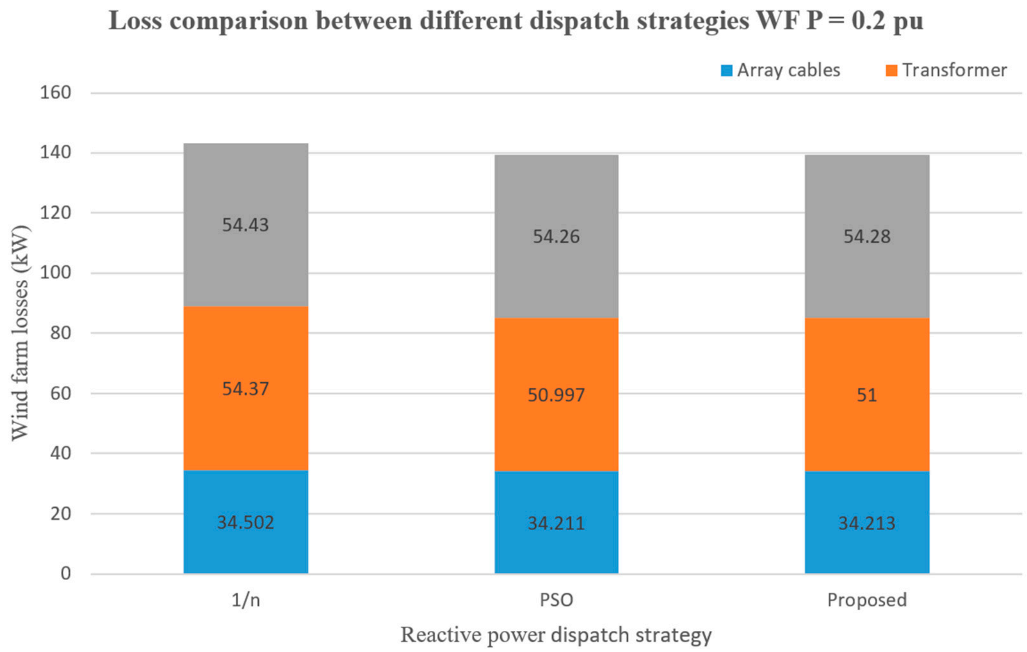


Figure 15. Comparison of power losses between dispatch algorithms in 20 MW output.

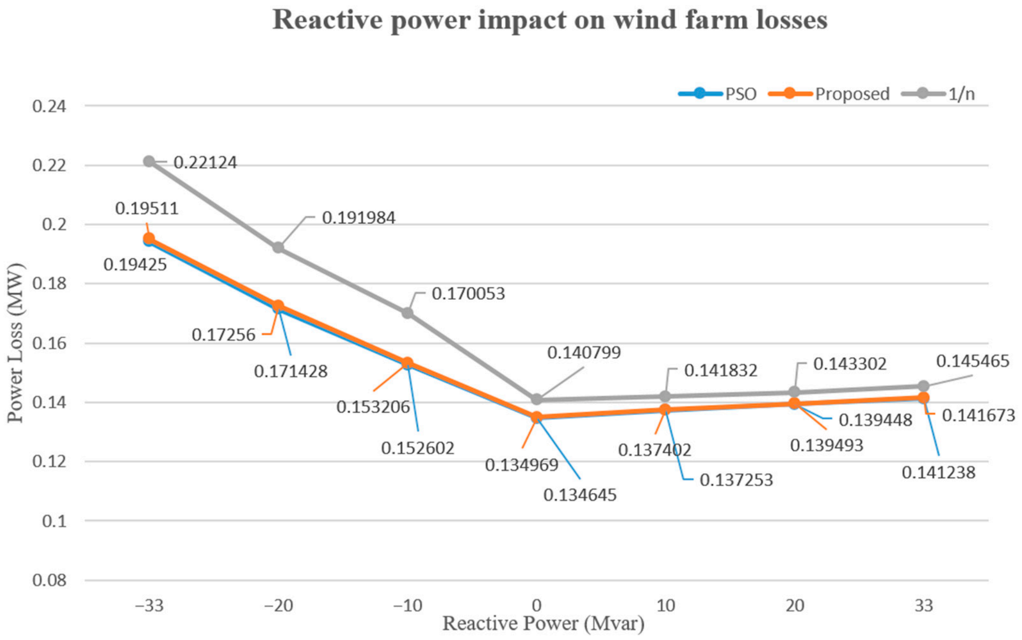


Figure 16. Reactive power impact on wind farm losses in 20 MW output.

5. Conclusions

This study has shed light on the critical issue of reactive power management in wind farms, introducing a novel methodology aimed at enhancing the efficiency of reactive power allocation among wind turbines.

In a comparative analysis with Particle Swarm Optimization (PSO), the proposed method, despite a marginal reduction in efficiency, has proven to be competitive. This suggests its capability to yield results that closely approach optimality.

The inherent drawbacks of PSO, such as its slow rate of convergence and sensitivity to initial parameters, render the proposed method especially appealing. It demonstrates robustness against initial conditions and achieves faster convergence to the optimal solution.

In summary, the proposed methodology stands as a promising avenue in the field of reactive power management for wind farms. Its merits, including stable convergence, superior solution quality, and ease of parameter tuning, position it as a viable candidate for practical implementation.

Author Contributions: All authors contributed to publishing this paper. S.-H.S. and G.-W.T. mainly proposed the algorithm of this paper. A.L. carried out the simulation tests, and he revised the original scheme. Writing was carried out by A.L., Y.-C.K., and S.-H.S. Final review was carried out by all authors. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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