Determination of Optimal Flexibility Potential for an Electrical Distribution Network

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Abstract: With the bidirectional power flows caused by the high infeed from renewable energy sources, the control of the traditional electrical energy system with meagre/no measurements in the distribution grids becomes ineffective. The implementation of protection and control functions on these active distribution grids becomes imperative. The project i-Automate deals with such a functional implementation of protection and control functions with the use of distributed measurements on a reusable standardized hardware platform. Optimal Power Flow (OPF) is one of the problems that need addressing in the active distribution grids to avoid network limit violations. In this paper, a first step is taken to implement OPF to determine the optimal flexibility usage on a Python platform and based on the results will be transported to the hardware setup.

Keywords: Distributed power generation, Power system dynamics, Grid automation, Optimal Power Flow, Voltage Regulation

1 Introduction

The introduction of renewable energy sources (RES) into the medium voltage (MV) and low voltage (LV) grids is converting the passive grids to active grids with bidirectional power flows. The amount of RES infeed is expected to extensively increase in the next few years [1]. The high infeed from RES also brings significant challenges to the operation and control of the distribution grids. The bidirectional power flows introduce complications such as voltage limit violations, line overloading, transformer overloading, to name a few. In order to solve the problems, there are certain actions that the distribution system operators could take.

The first possibility is to improve the overall network information situation by installing more measurement devices. The second option is to introduce smart network control through actuators for controlling the transformer taps and active power fed into the system to compensate primarily for the small voltage problems associated with active power peaks. The third option is the withdrawal and feed-in of the active power (P) in conjunction with the reactive power (Q) dispatch which is system-oriented. In the case of limit violations, control commands for the available actuators are then derived using an optimization algorithm.

The technical and regulatory requirements change rapidly. To react to these changes quickly and cost-efficiently, a flexible function adaption is required based on reusable hardware and software systems. In the research project i-Automate [1], [3], such a portable, modular and flexible system architecture is under development. Distributed measurements are acquired from different points of the distribution grid that are then processed in a State Estimation (SE) algorithm to identify the overall system state. The results of the SE algorithm are used as inputs in a voltage regulation algorithm [4] for solving any voltage violations in the grid.

This paper deals with the implementation of an optimal power flow (OPF) algorithm that could potentially replace the existing voltage regulation algorithm. As an initial step, the OPF algorithm is implemented in Pandapower to investigate the possibilities and challenges of the algorithm to be later implemented in the hardware device. The medium voltage (MV) network elements modelling employs Python as a primary programming language and Pandapower (Python) as a primarily open-source software framework for power flow analysis. An optimization algorithm (Interior Point Solver) is employed which satisfy the constraints and gives the best possible and most economical set points for remotely controllable actuators. These include the controllable inverters attached to the RESs feeding the active power (P), reactive power (Q), battery and energy storage systems (BESS) as well as the on-load tap changer (OLTC).

The structure of the paper is as follows. Section 2 deals with the optimization techniques and the OPF algorithm. Section 3 explains the stepwise methodology in which the implemented OPF algorithm in this study. Section 4 explains the case study while Section 5 deals with the results while the paper concludes with an outlook in Section 6.

2 Optimization in Power Systems

Optimization problems related to electrical energy systems can be broadly classified into two categories: power systems operation optimization and transmission-distribution planning optimization problems. Planning optimization problems include investigations in which optimal decisions related to the planning of new investments in certain transmission and distribution assets are carried out. For example, generation expansion planning comes under this category. While on the other hand, operation optimization problems usually deal with the optimization of the existing power plants and devices. The iterative multistep OPF method described in this paper belongs to the operation optimization problem, which translates to a cost-effective and reliable operation of the system.

Centralized and decentralized control strategies are vastly considered to mitigate network violations in literature. The decentralized strategies assume that the RES react to the local measurements under certain prerequisites [5] and these are also incorporated in the German grid codes [6]. Although, in the recent few years, the use of optimization algorithms in active distribution grids using deterministic [7], [8], non-deterministic [9] or hybrid methods [10] is taking a front seat. With the modern grid codes where volt-var control is possible [11], OPF with the proper use of flexibilities is a possible option for distribution-level grid control. In order to meet the variable load demands and to enhance the reliability and safety of the power system, the best operating levels of controllable elements can be determined and propagated through the network while keeping the operating costs as minimum as possible.

2.1 OPF algorithm

Generally, the OPF problem is a nonlinear programming problem with various input variables and nonlinear constraints such as in [8]. The optimization methods can be broadly classified into classic gradient-based methods and heuristic methods [12]. Most of the nature-inspired techniques come under the definition of heuristic techniques. Heuristic optimization techniques have different drawbacks. Initial population size greatly influences the efficiency and number of iterations for heuristic optimization. Greater the population size better is the solution space exploration. Although, the runtime and number of iterations increase. Parameter tuning and to decide whether the obtained solution is globally optimal or not is also a challenge in these techniques. Stopping criteria is difficult to establish for heuristic techniques because it is not always visible that the solution is globally optimal or not.

Classical methods belong to the well-researched and well-established subfield of nonlinear constrained optimization. There could be different drawbacks related to the classical methods, which include unsuitability for very large-scale optimization problems, and additional problems posed by non-convex constraints and integer variables. The iterative OPF method described in this paper uses an improved Quadratic interior-point solver implemented in Python, which comes under the category of the classic gradient-based method. This method has an advantage that fewer iterations are required as the termination conditions are met earlier and the solution is generally well centred within the feasible space set of constraints [13]. It helps determine the state of the power system, which translates to a cost-effective and reliable operation of the system. The operational and physical constraints include the line loadings, transformer loadings, voltage constraints, minimum and maximum output capability of generators and the maximum number of transformer stepping. The objective function that translates to cost minimization while satisfying the constraints is shown below:

Overall objective function:

$$Min\ F_g = \sum_{i=1}^{n} \left(a_i {P_{gi}}^2 + b_i P_{gi} + c_i + d_i {Q_{gi}}^2 + e_i Q_{gi} + f_i \right) + \Delta\,(t)^2 \qquad (1)$$

Constraints:

$$P_i^G - P_i^L = \sum_{j=1}^{N} V_i\, V_j\ [G_{ij} \cos(\theta_i - \theta_j) + B_{ij} \sin(\theta_i - \theta_j) \qquad i = 1\ to\ N \qquad (2)$$

$$Q_i^G - Q_i^L = \sum_{j=1}^{N} V_i\, V_j\ [G_{ij} \sin(\theta_i - \theta_j) + B_{ij} \cos(\theta_i - \theta_j) \qquad i = 1\ to\ N \qquad (3)$$

$$V_{min,j} \le V_j \le V_{max,j} \qquad j \epsilon bus \qquad (4)$$

$$\frac{V_i^2 + V_j^2 - 2\, V_i\, V_j\ \cos(\theta_i - \theta_j)}{Z_L(l)^2} - I_{L,max}^2(l)\ \le 0 \qquad l = 0,1,2 \ldots . Nl \qquad (5)$$

$$P_{min,gi} \le P_{gi} \le P_{max,gi} \qquad g \epsilon generator \qquad (6)$$

$$Q_{min,gi} \le Q_{gi} \le Q_{max,gi} \qquad g \epsilon generator \qquad (7)$$

$$P_{min,eg} \le P_{eg} \le P_{max,eg} \quad eg \epsilon\ ex\text{ternal}\ \text{g}rid \qquad (8)$$

$$V_{min,j} \le V_j \le V_{max,j} \qquad j \epsilon bus \qquad (9)$$

3 Implementation of the iterative algorithm

The objective function contains a combination of different available flexibilities. The optimization routine takes several stages to find the best possible solution. Initially, the Q from each RES is optimized. If the algorithm converges, the network violations could be solved only with the use of Q flexibility in the MV grid. In the case of non-convergence, P and Q flexibility for each RES is optimized by adding the P contribution of each RES in addition to Q flexibility into the cost function. In the case of non-convergence again, discrete transformer stepping is included as additional flexibility. Non-convergence from the last step theoretically means no optimization solution is available and the available flexibilities are insufficient. In this case, BESSs are added as additional flexibility in the system to further enhance the potential and to find the best optimal solution. This stepwise method to solve the network violations could also help establish the available P and Q, which could be transferred to the higher voltage levels, which is also another topic of research [13].

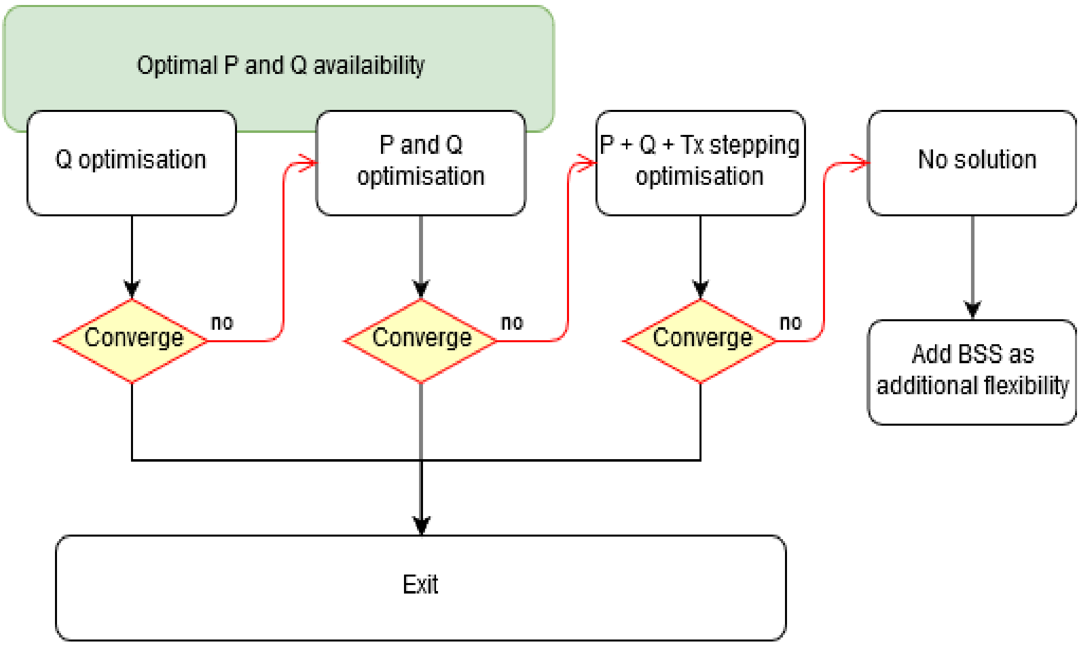

Figure 1: Stepwise implementation of OPF

Stage 1- Reactive power optimization

With the advancement of the smart inverter technologies, many possibilities arise to manage the voltage at the point of common coupling between the controllable generation and the electrical grid. One of them is to manage the available Q with or without curtailing the generated P. Q management without P curtailment is suggested in literature mainly because the cost for P curtailment is extensively larger. To reduce the costs and to fully utilize the available Q flexibility in the grid, the algorithm first optimizes Q. If the optimization converges to a possible solution, it means there is enough Q potential in the grid to mitigate the violations and the costs incurred by P curtailment can be avoided. The objective function at this stage only considers Q optimization, while taking the generated P as constant.

According to the recent MV interconnection requirements for PV cells in Germany, the power factor design criterion is specified to be 0.95 lag to lead [14]. This essentially means that the energy source should be able to inject or absorb Q approximately equal to 1/3 of the maximum P rating at each instance of time which translated to 32.87% of P_{max}. So for the purpose of optimization, the maximum and minimum Q constraints are taken to be approximately 33% of the maximum P at every instance of time. In the case of non-convergence, Q flexibility is insufficient and the other available flexibilities should be included in the optimization iteratively. The objective function subject to constraints takes the form:

$$Min\ F_g = \sum_{i=1}^{n} \left(d_i {Q_{gi}}^2 + e_i Q_{gi} + f_i \right) \qquad (10)$$

Stage 2- Active and Reactive power optimization

In case of no solution for Q optimization, P curtailment is the next step in the optimization process. Instead of connecting and disconnecting RES altogether from the system, smart inverters can be used to optimally control the P and Q output of RES thereby enhancing the productivity of the power system. Q is also optimized together because it results in an overall cost-effective solution for limit violations in the grid and results in a relatively lower P curtailment. No discrete transformer stepping is included at this stage. The objective function subject to constraints in such case becomes:

$$Min\ F_g = \sum_{i=1}^{n} \left(a_i {P_{gi}}^2 + b_i P_{gi} + c_i + d_i {Q_{gi}}^2 + e_i Q_{gi} + f_i \right) \qquad (11)$$

Stage 3- Transformer stepping as additional flexibility

In the case of non-convergence from the previous step, OLTC stepping is introduced as additional flexibility. Transformer steps introduce a discrete variable into the cost function and hence converts the nonlinear optimization to mixed-integer nonlinear programming. In order to avoid complex computations related to MINLP algorithms, transformer stepping is increased or decreased (depending on under-voltage or over-voltage) iteratively until the maximum or minimum stepping is reached, while performing the stage 1 and 2 with every iteration. Exhaustive search is concluded if there are no more violations remaining in the network. If there are more than one transformers in the network, the network is divided into areas depending on the transformer connection. Only the transformer connected to the area in which network violation is present is included as flexibility and all the other transformers are ignored to decrease the computation time. The overall cost function in such cases takes the form:

$$Min\ F_g = \sum_{i=1}^{n} \left(a_i {P_{gi}}^2 + b_i P_{gi} + c_i + d_i {Q_{gi}}^2 + e_i Q_{gi} + f_i \right) + \Delta\,(t)^2 \qquad (12)$$

Stage 4- Inclusion of BESS

In the case of non-convergence from stage 3, BESS is introduced as additional flexibility. This is done for two reasons. One is to make the optimization problem to converge and the other is to identify where a BESS might be required in case when an over-voltage or under-voltage problem occurs in the network which might not be possible to be solved with the use of the available flexibilities.

4 Case Study: CIGRE Medium voltage network

In this section, the network case studies and their results are studied. To demonstrate the results of the implemented OPF algorithm, a case study using the benchmark CIGRE medium voltage network [16] is undertaken. Situations where network violations like overvoltage, under-voltage or line overloading are simulated. The optimized power output of the RESs and the external grid are calculated such that the violations in the power grid are solved using the available flexibility in the grid.

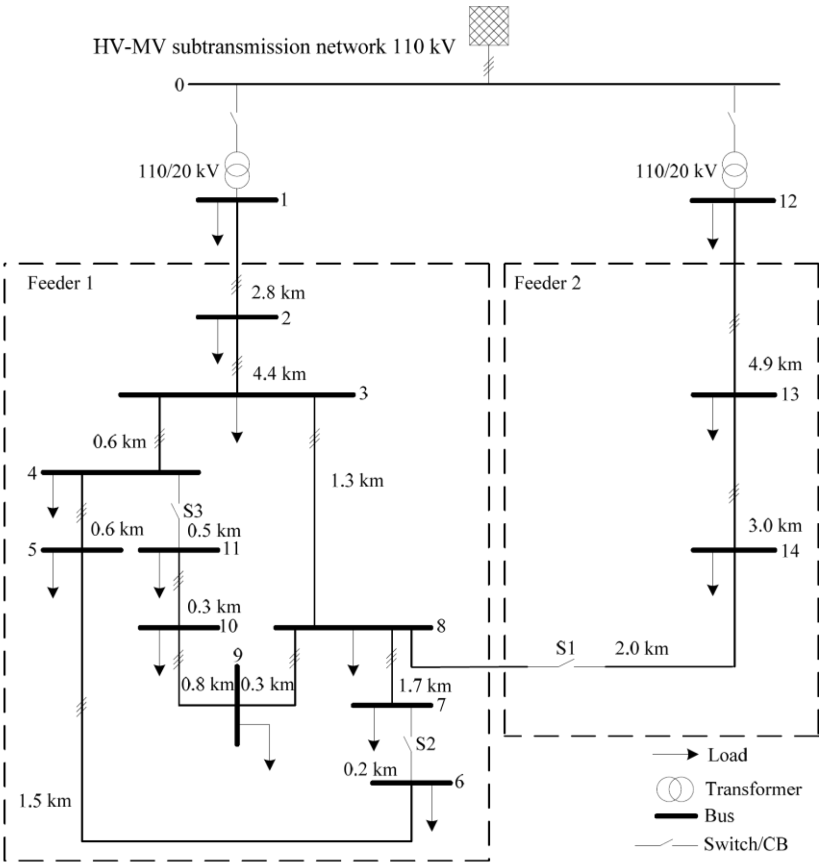

Figure 2: CIGRE MV Benchmark Grid [16]

4.1 Simulation scenarios

As one of the simulation scenarios, extreme high generation of RES and low loads is simulated to introduce high line overloading and overvoltage situations. As another scenario, high load and low RES generation are simulated to create an under-voltage situation. It must be noted that the optimization algorithm is invoked only when there is a violation in the grid, which include overvoltage or under-voltage, line overloading as well as transformer overloading. Even though the voltage limitations according to EN60150 specifies a voltage limit of ±10% for European grids, the initial limits for overvoltage and under-voltage are taken to be 1.06 per unit (pu) and 0.94 pu respectively. The limits for line overloading and transformer overloading are both taken to be 80% of the maximum capacity. The optimization algorithm gives the optimal solution set points for controllable network elements, which for the purpose of this particular case study includes RESs P and Q output as well as the transformer stepping. The network state is calculated after every 15 minutes and in case of violations, the optimal values for decision variables are communicated to solve network problems using the flexibility potential.

5 Results

This section deals with the results of the simulation. Though a lot of results were generated for each of the scenarios, only a select few are represented. The results of line loading, maximum voltage, P and Q of the RESs, P and Q required from the external grid are shown, while results such as transformer loading among others are not considered due to the page restrictions.

5.1 Line loading

Extreme line overloading situations were simulated in order to verify the effectiveness of the implemented algorithm. For the sake of simplicity, the figure shows only one line where the maximum line loading is simulated over the whole network. Fig. 3 shows the % of line loading before and after the optimization, along with the set limit.

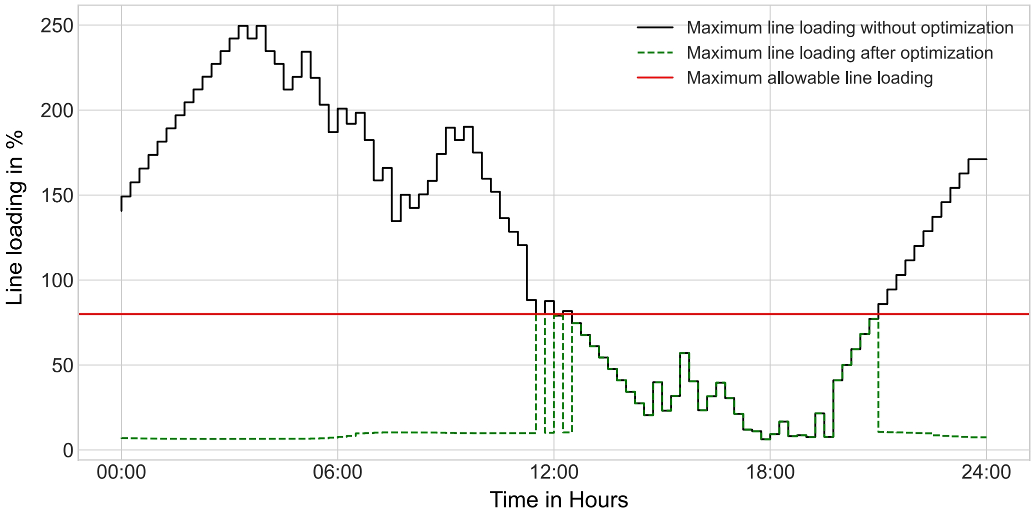

Figure 3: Line loading before and after optimization

5.2 Maximum voltage

Under the simulated conditions, overvoltage conditions were produced because of the higher generation and low demand load. After OPF, the voltage was regulated under the prescribed limits of 1.06 pu as in Fig. 4. There was no under-voltage violation with the simulated scenario.

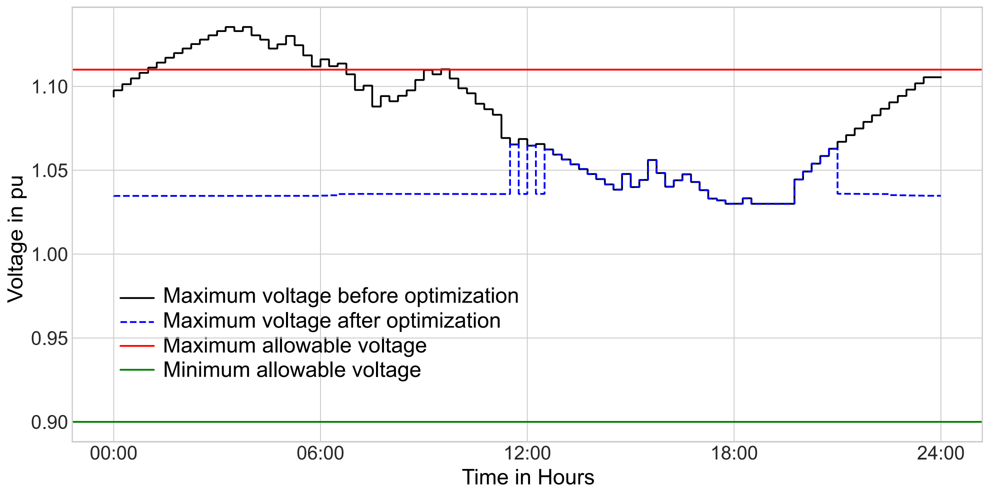

Figure 4: Maximum voltage of the line

5.3 Active and reactive power outputs from the RES

For an MV grid, both reactive and active power flow affects the voltage change and other anomalies because R/X for overhead lines in medium voltage network is nearly equal to 1 and the results can be seen in Fig. 5 and 6. For the sake of simplicity, only four of the RESs are shown here. As it can be seen, during high generation times, P is curtailed and Q is optimally dispatched to solve the network problems within the available flexibilities. It can be noted that without optimization, Q was at zero and the optimization uses the Q potential to overcome the violations in the grid. The Q support from the external grid is also reduced while the RESs provide Q support to the load locally to reduce the overall losses and economic costs as well as solving the overvoltage and thermal overloading in the network.

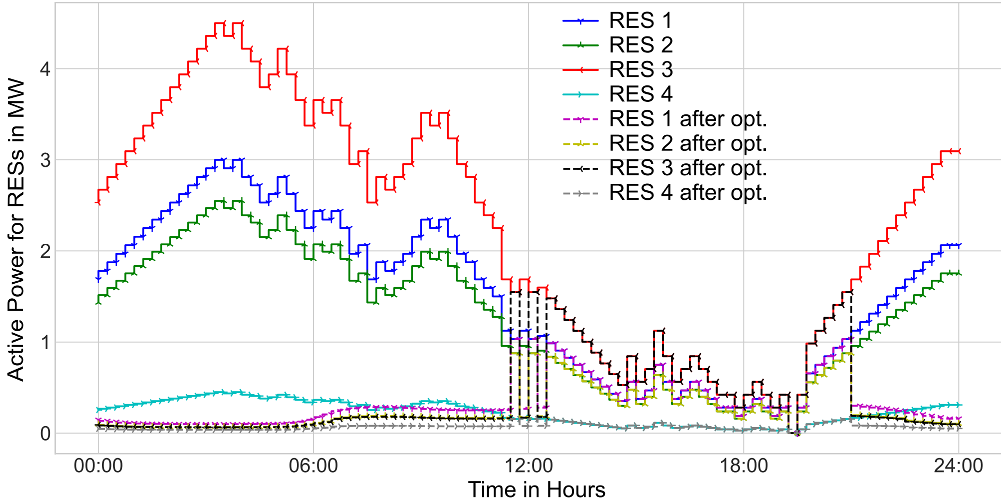

Figure 5: Active power of RESs

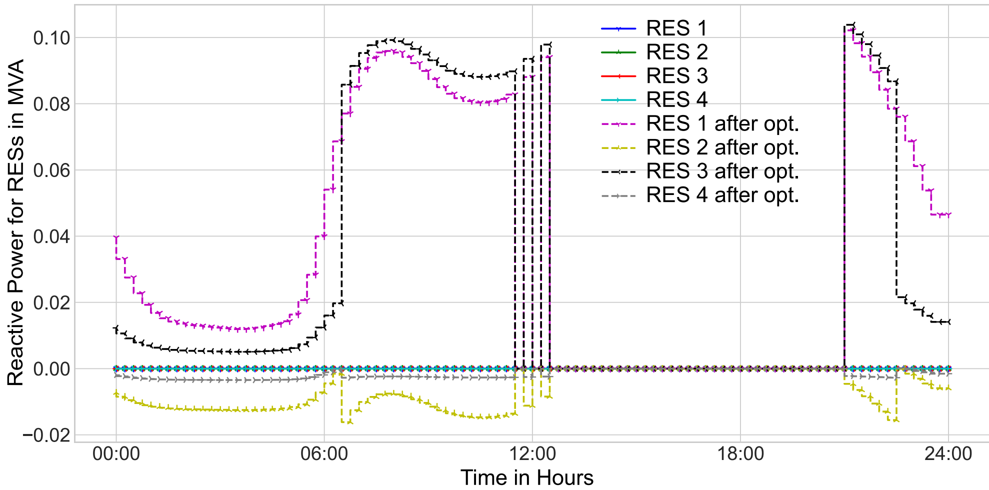

Figure 6: Reactive power of RESs

5.4 Active and reactive power outputs from the external grid

Since the objective is to use the generated power from RESs to the maximum capacity, the costs associated with the external grid are deliberately chosen to be higher than that of the RESs. Such costs effectively maximize the provision of P and Q from the local RESs while minimizing the P and Q from the external grid.

As can be seen in Fig. 7, initially without optimization, the excess P generation from the RESs resulted in increased reverse power flow to the external grid while the Q output of the RESs was equal to 0. The external grid was providing all the Q that was required by the loads. This led to a line overloading as well as transformer overloading. The implemented algorithm solves these issues and optimizes the P and Q output of the RESs so that minimal is required from the external grid, avoiding costs and utilizing the available flexibilities optimally.

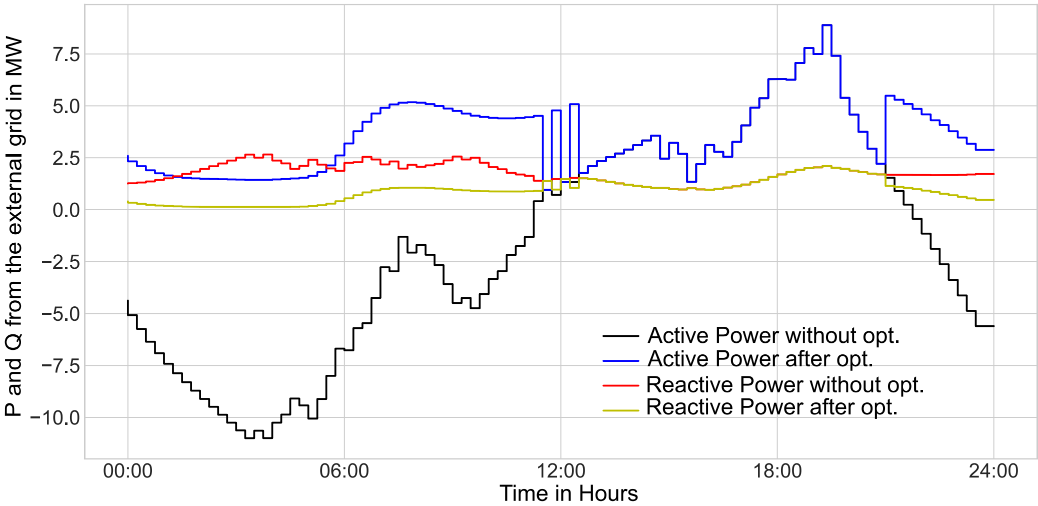

Figure 7: Active and reactive power from the external grid

6 Conclusion

The increasing share of RESs into the energy mix may lead to many network violations in addition to the overall unreliability of the system. The optimization algorithm described in this paper can be used to quickly search the available flexibilities in the grid and give the optimized control values for controllable elements. This way, the distribution system operators can delay the exhausting work of upgrading the network infrastructure and use the flexibilities to solve network limit violations while keeping the operating costs as low as possible.

In this work, an OPF algorithm was implemented and validated that could replace the existing voltage regulation algorithm available in the i-Automate devices. The advantage is that all the combination possibilities of the flexibilities are available to avoid limit value violations. Thus, the best possible solution could be found that is ideal in terms of the cost function that can be parameterized by the user, or at least close to the best solution. It must be noted that before practical use, the presented algorithm must be tested in the laboratory under realistic test conditions. It should be noted that this is only the first step and the OPF algorithm should be further implemented in the hardware devices to be validated in a laboratory setup with a real-time simulator and later in the field using real-world measurements. The algorithm is in the process of being converted in C++ to be imported into the hardware device. After successful validation and tests of the OPF algorithm using dynamic tests with the help of a real-time simulator, machine learning algorithms such as in [17] can be used to as a back-up in case the existing communication infrastructure encounters a problem. For practical implementation of the OPF algorithm, model predictive control could also be an interesting extension, the possibilities for which are also currently being investigated.

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