Comparison between the particle swarm optimisation and differential evolution approaches for the optimal proportional-integral controllers design during photovoltaic power plants modelling

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Abstract: This study deals with photovoltaic power plant modelling and its integration within the distribution network. It presents a simulation model of a whole photovoltaic power plant including the solar cells, boost converter with maximal power point tracking, voltage-oriented control and inductor-capacitor-inductor (LCL) filter. In such a sense, the applied inverter has many advantages such as a controllable power factor and sinusoidal input current, while the switching frequency of the power switch is relatively high. Therefore, it could cause high-frequency harmonics around the switching frequency. The traditional way of solving these problems is the usage of LCL filters, where the basic requirement is to achieve sufficient filtering with inductor and capacitor values as small as possible. In addition, emphasis is given to a comparison between two optimisation methods – particle swarm optimisation and differential evolution that are used for the parameters of proportional-integral (PI) controllers determination. These PI controllers represent the main part of the voltage-oriented control.

1 Introduction

The effort towards finding alternative energy resources for future energy sustainability is a priority issue nowadays [1, 2]. As conventional fossil-fuel energy sources diminish and the world’s environmental concerns about acid deposition and global warming increase, renewable energy sources are attracting more attention as alternative energy sources [3]. Thus the solar energy and appropriate photovoltaic (PV) power plants (or solar power plants) have become one of the important renewable energy sources [1, 2].

With the aid of various electronic power converters, mainly the direct current-boost converters and inverters, this kind of energy can be utilised and transported to the electric grid [2, 4]. On the other hand, from an operational point of view, a PV module may experience large variances of its output power under variable weather conditions resulting in problems of grid control [3–13].

PV energy can be generated for houses, intermediate-sized commercial installations or even for larger consumers of energy [5]. Within a residential PV system of a few kilowatts in size, the modules are mounted on the top of the roof taking into consideration the most suitable angle for maximum utilisation of the solar radiation intensity and temperature. Grid-connected systems can vary greatly in size (from a few kilowatts to several megawatts) but all consist of PV (or solar) modules, inverters and the other components such as wiring and module mounting structures [5]. This can be mainly attributed to the fact that cost per watt reduces as the size of the system increases [14].

PV modules are connected in series and in parallel to form strings and sub-arrays, which are further combined to feed the central inverters. The power conversion and grid integrations for megawatt scale PV power plants (PVPPs) become more complex as the size of the installations increase [14]. It has become a great challenge to ensure their operations at high availabilities, reliabilities and efficiencies. That is why the megawatt scale PVPPs have become a popular research topic over recent times, especially when focusing on medium-voltage grid integration, maximal power point tracking (MPPT) technology, multi-level inverters and so on, aiming for better utilisation of systems and resources [15, 16].

A grid-connected PVPP of hundreds of kilowatts scale is analysed in this paper. Such a PVPP converts the generated DC voltage to a regulated bus using a boost converter [17], which also performs MPPT [18–21]. This voltage is fed to an inverter to produce 250 V, which is then stepped up to 22 kV of medium voltage using a line transformer.

The applied inverter has many advantages such as a controllable power factor and a sinusoidal input current but the switching frequency of the power switch is about 2–15 kHz [22]. Therefore, it will cause high-frequency harmonics around the switching frequency. The traditional way of solving these problems is the usage of inductor-capacitor-inductor (LCL) filters [22–25] that have become more and more popular today. When designing an LCL filter, the basic requirement is to achieve sufficient filtering with inductor and capacitor values as small as possible [22].

This paper describes the complete procedure for a PVPP model’s design, where the main attention is paid to the proportional–integral (PI) controller parameters’ determination using two optimisation methods. These PI controllers represent the main part of the voltage-oriented control (VOC) [26–29]. The gains and time constants of PI controllers are defined by an optimisation procedure [30, 31], first by particle swarm optimisation (PSO) [32–35] and second by differential evolution (DE) [36, 37]. Finally, the results of both optimisation methods are compared. Similar approaches have been dealt with in several papers to date [20, 38, 39]. For example, there exist methods where PI control loops are eliminated from controlling and different methods for optimal tunings of controllers in grid-connected systems. In that sense the drawbacks related to the partial shading and rapidly changing irradiation conditions are improved [20, 38]. Using our approach the problems related to steady-state oscillations, as well as optimal MPPT controlling through partial shading, could be avoided. The aforementioned is confirmed by the PVPP integration within a model of the medium-voltage distribution network [40, 41], as a part of the distribution network in

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loop integration in the distribution network and its impact on power distribution are compared for the parameters obtained by both optimisation methods.

2 Model of PVPP

The system studied in this paper is shown in Fig. 1. It consists of solar cells, boost converter with MPPT, inverter with VOC, LCL filter and a transformer.

The output power of a solar cell is not only a function of the solar radiation level and the temperature but is also a function of the current and voltage product. By varying one of these two parameters, current or voltage, called MPPT, where calculations are compared with the measurements. In that sense both the solar cell, boost converter with MPPT, inverter with VOC, LCL filter and a transformer were performed to verify the results of the presented simulation model. In the taken case, one panel consists of two parallel branches of 60 series-connected cells.

Several MPPT methods can be used in order to maximise the output power of a solar cell while increase in operating temperature generally caused a drop in the module terminal voltage. It can be observed from the simulated and measured results that the photo current is proportional to the solar radiation level. As such, a higher solar radiation level will result in increased power output from the solar panel. Apart from that it is noted that the terminal voltage decreases with increasing temperature [11–13]. This effect is due to the band-gap energies of the semiconductor materials that reduce with decrease in temperature resulting in more electrons making it to the conduction band and hence a more efficient solar cell. In fact, the results showed a linear relationship between the short-circuit current and the solar radiation level, while there is a logarithmic relationship between the open-circuit voltage and the operating temperature.

The MPPT design was implemented and modelled, while the results showed that the tracker was able to maintain the operating point of the PV module at the maximum power point (MPP) thereby improving the amount of energy successfully extracted from the module.

2.1 Voltage-oriented control

Several control methods have been developed for voltage source converters (VSCs), from which one of the more popular is the VOC [26–29]. It provides high static and also dynamic performances via internal current control loops. All equations are transformed into new space vector coordinates, rotating synchronously with line voltage. It allows the advantage of finely using PI controllers [26]. Schematic presentation of VOC, as applied in this paper, is presented in Fig. 3.

Basically, the control strategy applied for the inverter consists of two control loops. Usually, there is an inner control loop which controls grid current and an external voltage loop which controls DC link voltage [29]. Input variables are current and voltage measured at the transformer high-voltage side (\(I_{TH}, U_{TH}\)), and the voltage of DC link \(U_{DC}\). On the basis of \(U_{DC}\) error, the external PI controller generates the reference value of the current in the \(d\)-axis \(I_{dref}\). Reference value of \(I_{dref}\) current was set to zero to fulfil the unity power factor condition [26]. For \(I_{d}\) and \(I_{q}\) error evaluation, the transformation of currents in \(dq\) coordinates system should be performed first. Within an aforementioned transformation performance the phase angle of grid voltage \(\theta\), evaluated by phase

\[
\frac{dI_{MPPT}}{dU_{MPPT}} + \frac{I_{MPPT}}{U_{MPPT}} = 0, \quad (4)
\]

where \(I_{MPPT}\) and \(U_{MPPT}\) stand for the input current and the input voltage of MPPT algorithm, respectively (Fig. 1) obtained by (5) and (6), where \(I_{PH}\) stands for the photo current, \(I_{D}\) is the direct current, \(U\) is the diode voltage, while parallel resistance \(R_{p}\) and series resistance \(R_{S}\) represent the leakage currents in the diode and the losses due to the contacts and the connections

\[
I_{MPPT} = I_{L} = I_{PH} - I_{D} - \frac{U}{R_{p}}, \quad (5)
\]

\[
U_{MPPT} = U - I_{L} R_{S}, \quad (6)
\]
lock loop, should be defined [26]. Additionally, apart from current, the grid voltage must be transformed in the \(dq\) coordinates system \((U_{d}, U_{q})\), while even better dynamic response could be reached by the compensation of the filter parameters \(RL_{\text{filt}}\). The current errors are delivered to the internal PI controller. Its output generates together with the modified \(U_{d}, U_{q}\) commanded VSC voltages \(U'_{d}, U'_{q}\). After backward transformation the three voltages are delivered to the pulse width modulation modulator, which generates switching signals for the inverter.

Another important part of the presented control system is the PI controllers. Procedures for the voltage and current controller parameters’ determination may be based on different methods such as symmetrical optimum, the Ziegler–Nichols method or even on the optimisation algorithms’ applications. The optimisation procedure was applied in this paper (its detailed description is provided in Section 3).

### 2.2 LCL filter

To reduce the current higher harmonics around the switching frequency, sometimes a high value of input inductance is used. However, for applications above several kilowatts, it becomes too expensive to realise higher values of inductance. Sometimes a high value of input inductance is used to reduce the current higher harmonics around the switching frequency, sometimes a high value of input inductance is used. However, for applications above several kilowatts, it becomes too expensive to realise higher values of inductance.

### 3 Optimisation methods

When all parameters are defined as described in Section 2, the PI controllers’ parameters may be calculated. Basically, there are two PI controllers, the external DC voltage controller and internal current controller, with appropriate gains and time constants. In this work, the optimisation procedure was applied for determining all PI controllers’ parameters [22]. Within the optimisation process the four parameters should be defined, two gains \((K_{u}, K_{i})\) and twice constants \((T_{u}, T_{i})\), respectively.

The mentioned optimisation problem could be solved by the different optimisation algorithms, such as genetic algorithm, DE, PSO, the firefly algorithm and so on. [30, 31]. Two methods, DE [36, 37] and PSO [32–35] were used and compared in this work. Both were chosen for their simple and effective working, which do not require the models’ mathematical descriptions or differentiations [33].

#### 3.1 Particle swarm optimisation

PSO is an evolutionary technique developed by Kennedy and Eberhart. It is initialised with a population of random solutions called particles that are associated with a velocity [32]. In that manner particles fly through the search space with velocities that are dynamically adjusted. Basically, particles have a tendency to fly towards an optimal solution. In our case each particle \(i\) is defined as a potential solution of the optimisation problem within a four-dimensional space, so it is associated with position \(P_i\)

\[
P_i = (K_u, K_i, T_u, T_i).
\]

The PSO algorithm basically maintains a swarm of particles, where each individual particle represents a solution. In that manner, particle follows a behaviour, which emulate its own achieved successes and success of neighbouring particles. In order to understand aforementioned rule, the best point found by the particle in its past life and the global best point found by the swarm of particles in their past life should be recorded. Therefore, the position of a particle is influenced by the best position encountered by itself and the best position in the whole swarm.

In that manner, the PSO algorithm renews its position \(p_{\text{new}}\) and velocity \(v_{\text{new}}\) to search the whole state space using (8) and (9), where \(P\) stands for the position of the particles in the previous times. Therefore, \(v_{\text{new}}\) and \(V\) are the velocities of the particles in present and previous times, \(p_{\text{best}}\) being the present position of the particles, \(p_{\text{gast}}\) the partial optimal solutions and \(G_{\text{best}}\) the global optimal solutions, whereas \(\lambda\) is the weighted (inertia) factor which has a range from 0.1 to 0.9, while \(c_1\) and \(c_2\) are acceleration (cognitive and social) coefficients [19, 35]. Additionally, rand() is random numbers sample from \([0, 1]\). An individual particle’s new position is therefore associated with (9)

\[
v_{\text{new}} = \lambda V + c_1 \text{rand}() (P_{\text{best}} - P) + c_2 \text{rand}() (G_{\text{best}} - P) \tag{8}
\]

\[
p_{\text{new}} = P + v_{\text{new}} \tag{9}
\]

Therefore, according to (8), the movement of particles in the optimisation process could be described by three terms (Fig. 4). The first term represents an inertia factor, where the particle keeps moving in the direction it had previously moved, while the second and third terms represent the memory and information exchange segments. It should be mentioned that inertia weight factor could be fixed, linearly decreased or randomly changed during the optimisation process. Similarly, even acceleration coefficients could be time varying, where \(c_1\) is decreased linearly and \(c_2\) is increased linearly over time [35].

In comparison with some other evolutionary techniques, the PSO algorithm could provide better computational efficiency, so it requires less memory space and speed of the central processing.

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*Fig. 3 Schematic presentation of applied VOC*

*Fig. 4 Movement of particle within an optimisation process*
unit. The advantages are that it is intelligent, simple, fast and robust. Apart from that, it has no overlapping and mutation calculation therefore a particle is not tested multiple times, and performs well in situations where the objective function is complicated and not continuous. The disadvantages are that the method easily suffers from partial optimism, which causes the loss of accuracy during regulation of its speed and direction [33, 34].

Since the last decade, PSO has gained much attention and wide applications within different fields, for example inside algorithms when tracking the MPP using the direct control technique, inside hybrid active power filter used to compensate for total harmonic distortion in three-phase four-wire systems, for radial basis function neural networks, for solving the optimal distribution system reconfiguration problem for power loss minimisation, for economic load dispatch or used for choosing suitable controlling parameters of the kernel function and so on. [20, 32, 35]. Similar to the presented paper, it was shown, to illustrate the application of the PSO algorithm in tracking the MPP using the direct control technique that with proper choice of control parameters, a suitable MPPT controller can be easily designed [20].

3.2 Differential evolution

The DE algorithm was introduced in 1995 by Storn and Price [36]. It has become one of the more frequently used evolutionary algorithms when solving the global optimisation problems, even those dealing with technique [37]. Therefore, DE has gained much attention and wide applications within different fields, especially due to its effectiveness in dealing with difficult optimisation issues, as well as simplicity of implementation. The DE works with the beginning population and the crossover population, which are of the same size [36]. The population size depends on the number of population members NP and the number of seeking parameters D (7). The beginning population is chosen completely randomly, while crossover population is obtained from beginning population in the manner, described by

$$i = 1, \ldots, NP, \quad j = 1, \ldots, D$$

$$u'_j = \begin{cases} \nu_j + F (\nu_i - \nu_r^j) & \text{if } \text{rand}[0, 1] \leq \text{CR or } j = k \\ \nu_j & \text{otherwise} \end{cases}$$  \hspace{1cm} (10)$$

where $F \in [0,2]$ and $CR \in [0,1]$ are DE control parameters which are kept constant during optimisation, $\nu_i, \nu_r, \nu_r^i \in \{1, \ldots, NP\}, \nu_i \neq \nu_r^i \neq \nu_i$ are randomly selected vectors from the population $\nu_\text{pop}$, different from each other and different from the current vector with index $i$, and $k \in \{1, \ldots, D\}$ is a randomly chosen index. Index $j$ is chosen for each parameter from (7), while $u$ and $x$ are new and previous individual members of populations, respectively. After that, during the selection, all members of crossover population are compared with the members of the beginning population, where members with better objective function value are chosen for composing the new population, which replaces beginning population.

4 Parameters of the PI controller’s determination

The procedure described in Sections 2 and 3 was applied on an example of a 100 kW PVPP. Within computing the output transformer (Fig. 1), with the same power 100 kW and voltage ratio 240 V/22,000 V was applied. After a desired inductor ripple current $\Delta i_1 = 3\%$ a desired output voltage ripple $\Delta v_{\text{OUT}} = 2\%$, a minimum switching frequency of the boost converter $f_s = 4000$ Hz, an input voltage $U_{\text{IN}} = 250$ V and the desired output voltage $U_{\text{OUT}} = 500$ V had been set, both $L_1 = 3.68$ mH and $C_1 = 589.5$ µF, were calculated. Additionally, with $f_{\text{VSC}} = 2500$ Hz, the filter parameters $L_2 = 0.1833$ mH, $L_3 = 0.916$ mH and $C_f = 276.3$ µF were determined.

Finally, using the optimisation procedure, first with PSO and second with DE, the parameters of PI controllers were defined. The dimension of problem is $D = 4$. Other parameters of PSO were set at $\lambda = 0.9, c_1 = 0.15, c_2 = 1.2$ and size of the swarm $N_{\text{sw1}} = 40$, while the parameters of DE were equal to $F = 0.7, \text{CR} = 0.5$ and $NP = 40$. In the objective function (10) the step responses on four different solar radiation (650, 800, 900 and 1000 W/m$^2$) levels were included. The results obtained by both methods, within the same computational time, are presented in Figs. 5 and 6, and in Table 1. During these calculations 1000 iterations were evaluated by DE and 670 iterations by PSO. Fig. 5 shows the output power and input MPPT current of the PVPP, and Fig. 6 shows the input and output voltages of boost converter for different solar radiation levels. The presented results were first obtained by PSO and second by DE. The presented results have shown that DE, within the same computational time, provides better results. The PSO algorithm was then applied again, this time with a twice higher size of the swarm $N_{\text{sw2}} = 80$. After the same iteration evaluation as the first time and twice higher computational time the results were obtained and are presented in Fig. 7 and Table 2. Having twice higher size of the swarm the results are acceptable and are comparable with the results obtained by DE. These statements are possible to confirm even by measurements on a real PVPP. The area of the chosen PVPP was about 670 m$^2$, while the number of PV panels was equal to 410. The type of grid-connected PV inverter was ‘string’, where several strings of PV panels were operating within a parallel connection. Output powers calculated by the aforementioned models (PSO and DE) are compared with the measured ones in Fig. 8. In that sense, the

![Fig. 5](image-url) Output power and input MPPT current of the PVPP for different solar radiation levels – PSO ($N_{\text{sw1}}$), and output power and input MPPT current of the PVPP for different solar radiation levels – DE.
Fig. 6  Input and output voltages of the boost converter for different solar radiation levels – PSO ($N_{sw}$), input and output voltages of the boost converter for different solar radiation levels – DE

| t, s | 0.04 | 0.06 | 0.08 | 0.1  | 0.12 | 0.14 | G, kW/m² |
|------|------|------|------|------|------|------|----------|
| PSO ($N_{sw}$) | $P$, kW | 55.7 | 62.7 | 64.5 | 59.3 | 62.8 | 65.2 | 0.65 |
| PSO ($N_{sw}$) | $P$, kW | 78.0 | 82.1 | 81.1 | 80.8 | 81.3 | 81.2 | 0.8 |
| PSO ($N_{sw}$) | $P$, kW | 89.2 | 92.9 | 91.9 | 91.7 | 91.9 | 91.8 | 0.9 |
| DE | $P$, kW | 99.3 | 100.8 | 101.5 | 86.2 | 69.9 | 101.4 | 1 |
| DE | $P$, kW | 58.2 | 63.9 | 64.9 | 64.6 | 65.2 | 64.6 | 0.65 |
| DE | $P$, kW | 75.7 | 81.6 | 80.9 | 81.2 | 81.0 | 81.0 | 0.8 |
| DE | $P$, kW | 85.6 | 92.4 | 91.8 | 91.8 | 91.8 | 91.8 | 0.9 |
| PSO ($N_{sw}$) | $P$, kW | 95.5 | 103.3 | 102.9 | 102.4 | 102.4 | 102.7 | 1 |
| PSO ($N_{sw}$) | $P$, kW | 245.1 | 238.4 | 245.5 | 248.6 | 234.8 | 234.4 | 0.65 |
| PSO ($N_{sw}$) | $P$, kW | 301.6 | 292.2 | 292.4 | 297.8 | 292.5 | 292.5 | 0.8 |
| PSO ($N_{sw}$) | $P$, kW | 341.9 | 331.0 | 331.3 | 331.1 | 331.3 | 331.2 | 0.9 |
| PSO ($N_{sw}$) | $P$, kW | 331.1 | 349.0 | 359.3 | 334.7 | 376.6 | 367.8 | 1 |
| DE | $P$, kW | 246.3 | 233.6 | 243.3 | 242.4 | 234.5 | 240.2 | 0.65 |
| DE | $P$, kW | 303.3 | 293.1 | 298.1 | 292.5 | 292.5 | 300.6 | 0.8 |
| DE | $P$, kW | 342.0 | 331.6 | 331.7 | 331.3 | 331.3 | 331.2 | 0.9 |
| DE | $P$, kW | 379.9 | 370.2 | 369.6 | 370.1 | 369.8 | 369.1 | 1 |
| PSO ($N_{sw}$) | $i_{MPPT}$, A | 245.1 | 238.4 | 245.5 | 248.6 | 234.8 | 234.4 | 0.65 |
| PSO ($N_{sw}$) | $i_{MPPT}$, A | 301.6 | 292.2 | 292.4 | 297.8 | 292.5 | 292.5 | 0.8 |
| PSO ($N_{sw}$) | $i_{MPPT}$, A | 341.9 | 331.0 | 331.3 | 331.1 | 331.3 | 331.2 | 0.9 |
| PSO ($N_{sw}$) | $i_{MPPT}$, A | 331.1 | 349.0 | 359.3 | 334.7 | 376.6 | 367.8 | 1 |
| DE | $i_{MPPT}$, A | 246.3 | 233.6 | 243.3 | 242.4 | 234.5 | 240.2 | 0.65 |
| DE | $i_{MPPT}$, A | 303.3 | 293.1 | 298.1 | 292.5 | 292.5 | 300.6 | 0.8 |
| DE | $i_{MPPT}$, A | 342.0 | 331.6 | 331.7 | 331.3 | 331.3 | 331.2 | 0.9 |
| DE | $i_{MPPT}$, A | 379.9 | 370.2 | 369.6 | 370.1 | 369.8 | 369.1 | 1 |
| PSO ($N_{sw}$) | $u_{INP}$, V | 262.0 | 276.2 | 261.0 | 244.2 | 280.6 | 281.1 | 0.65 |
| PSO ($N_{sw}$) | $u_{INP}$, V | 267.4 | 281.6 | 281.3 | 274.7 | 281.3 | 281.3 | 0.8 |
| PSO ($N_{sw}$) | $u_{INP}$, V | 264.0 | 281.6 | 281.4 | 281.6 | 281.6 | 281.5 | 0.9 |
| PSO ($N_{sw}$) | $u_{INP}$, V | 302.0 | 295.3 | 289.9 | 300.6 | 273.0 | 283.6 | 1 |
| PSO ($N_{sw}$) | $u_{INP}$, V | 257.7 | 281.7 | 267.3 | 267.3 | 269.3 | 269.9 | 0.65 |
| DE | $u_{INP}$, V | 262.9 | 280.7 | 274.2 | 281.3 | 281.3 | 269.6 | 0.8 |
| DE | $u_{INP}$, V | 263.5 | 281.0 | 281.0 | 281.4 | 281.2 | 281.4 | 0.9 |
| DE | $u_{INP}$, V | 266.5 | 281.4 | 282.0 | 281.9 | 281.7 | 282.4 | 1 |
| PSO ($N_{sw}$) | $u_{OUT}$, V | 503.4 | 504.7 | 501.2 | 502.9 | 503.7 | 500.8 | 0.65 |
| PSO ($N_{sw}$) | $u_{OUT}$, V | 507.2 | 502.4 | 502.8 | 503.3 | 502.4 | 501.4 | 0.8 |
| PSO ($N_{sw}$) | $u_{OUT}$, V | 515.0 | 504.5 | 504.7 | 474.2 | 511.0 | 504.4 | 1 |
| DE | $u_{OUT}$, V | 506.0 | 503.8 | 502.0 | 503.2 | 501.7 | 502.9 | 0.65 |
| DE | $u_{OUT}$, V | 504.2 | 501.4 | 501.6 | 501.9 | 501.5 | 501.6 | 0.8 |
| DE | $u_{OUT}$, V | 503.7 | 501.6 | 502.2 | 502.1 | 501.4 | 501.5 | 0.9 |
| DE | $u_{OUT}$, V | 506.2 | 502.0 | 500.4 | 501.1 | 502.0 | 501.3 | 1 |

Fig. 7  Output power and input MPPT currents of the PVPP for different solar radiation levels – PSO ($N_{sw}$), input and output voltages of the boost converter for different solar radiation levels – PSO ($N_{sw}$)
measured values of solar radiation $G$ and temperature $T$ (Fig. 8) represented the input values of the applied models (Fig. 1).

In the aforementioned case of 22nd August, the daily average solar radiation level was about 600 W/m$^2$, peaking at 950 W/m$^2$. The calculated power output curve followed the measured values' trend reasonably well, especially where the parameters of the PI controllers were defined by DE and PSO with a twice higher size of the swarm. In the morning, the simulated and the measured power output increases gradually and coincides with the solar radiances level intensity. However, obvious difference between the power curves could be seen around the early and late hours. Such differences were mainly caused by spectral and reflection effects that are not considered within the presented model.

It can be concluded that although there exist more complex models of the PV cell, this is the preferable choice in terms of accuracy, its computational requirement is much more demanding in comparison with the chosen (simple and well-known) model that offers a reasonable compromise between computational complexity and accuracy, and hence was selected for this study. The criterion of computational time was especially important in the presented case, where the optimisation method with objective functions was an important part of the entire study.

### 5 PVPP connected to a distribution network

The described PVPP was first included within the medium-voltage distribution network, as part of the distribution network in loop operation [40, 41]. The discussed medium-voltage network is shown in Fig. 9. It consists of a substation at Krsko, Slovenia with two 40 MVA 110 kV/22 kV Dyn transformers equipped with tap changer units [40]. They supply the busbars S1 and S2; M3 and M4 are the measurement points. The two feeders connected to the busbars S1 and S2 are used to form the closed loop. The network structure of the discussed feeders is schematically presented in Fig. 9 [40], where other measurement points (M31 and M41) are also presented. In Fig. 9 location of PVPPa shows the placement of an additional PVPP, which could be switched-off or switched-on.

Fig. 10 presents the power distribution through the network (points M3, M31, M4 and M41), for the PVPP parameters obtained by both optimisation methods. The results obtained by PSO algorithm are shown for the sizes of the swarm $N_{sw1}=80$ and $N_{sw2}=40$. The solar radiation $G_1$ (Fig. 11) is set as a variable input parameter.

It is clear that in the case of higher solar radiation the power at measurement points M3 and M4 was lower than in the case of lower solar radiation. The reason was that part of the energy for the feeder connected to the busbar S1 was delivered from the PVPP. It is clear from Fig. 10 that the results obtained by PSO ($N_{sw}$) provided unreliable results (agreement with DE values $\approx 90\%$), especially in the case of solar radiation levels lower than 500 W/m$^2$. Otherwise, the results obtained by DE and PSO ($N_{sw}$) gave acceptable results (agreement 98.5%), while the computational effort in the case of DE application was lower.

It should be stressed that in the presented case only PVPP was included within the model, while additional PVPPs was excluded
Fig. 9  Substation Krsko’s applied distribution network

Fig. 10  Powers at the points M3 and M31, powers at the points M4 and M41

Fig. 11  Solar radiation – input parameter
from it. Otherwise, Fig. 12 presents the results where additional PVPPa was switched on. In that case with an additional source within the distribution system, where the amount of energy from the substation was decreased, the results obtained by PSO \((N_{sw})\) had better (agreement 94%) but still not comparable with the results obtained by PSO \((N_{sw2})\) and DE.

The described PVPP was second included within the low-voltage distribution network as part of the distribution network during radial operation (Fig. 13). The results are presented in Fig. 14. In that case both solar radiations \(G_{c1}\) and \(G_{c2}\) (Fig. 11) were set as the variable input parameter, while additional PVPPa was switched-off (above) or switched-on (below). In the case of higher solar radiation the power at the measurement point \(M\) was lower than in the case of lower solar radiation. Therefore, the part of the energy for loads was delivered from the PVPP.

It is clear that the results obtained by DE and PSO with twice higher size of the swarm \(N_{sw2}\) were acceptable (values of agreement were higher than 99%), while the results of PSO with the lower size of the swarm \(N_{sw}\) were worse (agreement 95%). This was explicitly clear in the case of lower solar radiation. When using a different input curve of solar radiation marked as \(G_{c2}\) the aforementioned was even more expressed (agreement 85%), while even the results obtained by PSO with twice higher size of the swarm \(N_{sw2}\) could not provide completely acceptable results (agreement 95.4%), so the size of the swarm (and consequently computational time) should be additionally increased.

Additionally, from the presented cases it is possible to conclude that higher amounts of energy delivered from the PVPP generally means better results.

6 Conclusion

This paper presented PVPP modelling and its integration within a distribution network. The paper mainly focused on comparing two optimisation methods, PSO and DE. The PI controllers, as a main part of VOC, were determined using both methods. In addition, the whole procedure for PVPP modelling with solar cells, boost converter with MPPT, VOC and LCL filter inclusion, was presented in Section 2. It is obvious that appropriate results could be obtained by both PSO and DE optimisation methods, while the computational effort in the first case is higher. The described procedure of PVPP modelling could be used within the different evaluations of PVPPs’ impacts, for example, on the additional losses in distribution networks, on the power quality factors, inside smart grids’ operations or virtual power plants’ modelling and so on. It has been shown that DE provides acceptable results in lower computational time than the PSO algorithm. This fact is especially
important in cases where the computational time for the objective function evaluation is relatively high.

7 References

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