Operation chart study of multi-inverter photovoltaic power plant connected to medium voltage grid

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Abstract—The article presents model for development of realistic operation chart, i.e. P-Q diagram, at point of common coupling of photovoltaic power plant, comprised of multiple inverter units, connected to medium voltage grid. Structure and components of common multi-inverter photovoltaic power plant connected to medium voltage is analyzed. Contributions of all plant components to total active and reactive power are theoretically determined. On base of that analysis P-Q diagram of all possible plant operation points at the point of common coupling is defined. Measurements conducted on real case study plant are used for comparison with calculated values and for necessary corrections to the model.

Keywords—inverter, medium voltage, operation chart, photovoltaic plant, P-Q diagram

I. INTRODUCTION

Multi-inverter photovoltaic plants connected to MV grid have specific configuration with multiple sources connected to LV side, but the generated power is transmitted through unit transformer to MV side where the point of common coupling to the grid is established. There are two types, one with few centralized inverters of large power rating and other with many inverter units of smaller power ratings. The practical experience has shown that the requests for connection are mainly for the plants with multiple smaller inverter units which are standardized products and economically more preferred by investors [1]. Power plant is usually connected to one of the existing MV feeders spreading from the HV/MV substation, on which are already connected several MV/LV consumer substations with its consumption. The connection is made through two objects: power plant substation and distribution network operator (DNO) connection substation [2]. The point of common coupling (PCC) of the power plant to the operator's electrical grid is in system operator connection substation, in switchgear bay where the cable to the power plant substation is connected.

II. SUBSTITUTE MODEL

Principle diagram of such solar photovoltaic plant is shown on Figure 1. In accordance with stated in introduction, it is possible to create substitute model for a plant shown on Figure 1, so that this model encompasses the complete inner power plant grid with all the inverters, LV cables, transformer and MV cable to interface substation (the point of common coupling with the grid).

Substitute model of the power plant can be used to define the plant at the point of common coupling (interface with the grid) with two characteristic values: active and reactive power (delivered to or consumed from the grid) at that point.

III. OPERATION CHART

Considering that power plant point of connection to grid is in DNO interface transformer substation, in outgoing bay feeding the power plant transformer substation [2], and considering substitute model from previous chapter, such model of distributed source at the point of connection can be used to define “operation chart” of the power plant, i.e. P-Q diagram showing area of possible operation points. It is important to emphasize that inverters, as primary source in this type of power plants, have adjustable power factor. Some manufacturers give the capability for production of active and reactive power for its products by means of capability curves in P-Q diagram, for the maximum apparent power operation points, as shown on Figure 2.
IV. CONTRIBUTION OF INDIVIDUAL ELEMENTS

Power generated by photovoltaic panels, transferred from DC to AC voltage grid by inverters is major contributor to the value of active power of the power plant. The other elements on the AC grid side generate losses of it, due to dissipation on resistances of elements.

Total value of reactive power of the power plant is influenced by all elements. Specific status for inverters must be considered (power factor setting to 1 is most likely). The other elements are basically: power transformer (contribution to inductive reactive power) and low voltage and medium voltage cables (contribution to capacitive reactive power). Specific case is with photovoltaic plants having inverters without galvanic isolation of AC and DC side (which is often the case) where parasitic capacitances of photovoltaic panels are transmitted to AC side [5]. Depending on the size of solar panel fields and the mounting details this capacitive reactive power can be significant during night work of the power plant when it dominates (especially with smaller power plants).

V. ACTIVE POWER (P) OF THE POWER PLANT AT PCC

A. Inverters

In this type of plants inverters are "generators" of energy. DC part of system in which the source are PV cells is technology part and not of interest in this research. From AC side, inverters deliver electrical power to the grid and are considered as AC electrical energy source.

Considering the fact that investor to the power plant usually wants to economically optimize generation, power factor of the inverters would be always set to 1. But inverters, have flexible options of generating active and reactive power, as can be seen on Figure 2. Depending on power factor set, active power is different. The value of generated active power of inverter is given by:

\[ P_{\text{inv}} = S_{\text{inv}} \cdot \cos \phi_{\text{inv}} \]  \( \text{(1)} \)

where \( P_{\text{inv}} \) is active power of individual inverter, \( S_{\text{inv}} \) is apparent power of individual inverter and \( \cos \phi_{\text{inv}} \) is power factor set in individual inverter.

Therefore, total influence of all inverters to active power of the power plant is sum of individual inverter active powers in given moment:

\[ P_{\text{inv-tot}} = \sum_{i=1}^{n} P_{\text{inv-i}} \]  \( \text{(2)} \)

where \( P_{\text{inv-tot}} \) is total generated active power of all inverters in given moment. The highest total active power is equal to sum of all rated inverters active powers:

\[ P_{\text{inv-tot-max}} = \sum_{i=1}^{n} P_{\text{inv-i-nom}} \]  \( \text{(3)} \)

where \( P_{\text{inv-tot-max}} \) is maximum possible total active power of all \( n \) inverters and \( P_{\text{inv-i-nom}} \) is rated active power of individual inverter.

B. Low voltage cables

On low voltage cables there is a dissipation of active power flowing through these cables, on cable resistances. The losses on individual cables can be calculated from:

\[ \Delta P_{\text{cable-i}} = \sum_{k=1}^{n} R_{\text{cable-i}} \cdot I_{\text{current-i}}^2 \]  \( \text{(4)} \)

where \( \Delta P_{\text{cable-i}} \) is active power losses on cable \( i \) (cable section \( i \)), \( R_{\text{cable-i}} \) is resistance of cable section \( i \), \( I_{\text{current-i}} \) is current through cable section \( i \), \( P_{\text{cable-i}} \) is active power flow through cable section \( i \), \( V \) is phase voltage (LV), \( k \) is portion of momentary active power in maximum total possible active power (rated active power) and \( P_{\text{cable-i-nom}} \) is rated active power, maximum possible power expected to flow through individual cable (cable section).

Value of resistance of cable section \( i \) can be determined from known cable parameters:

\[ R_{\text{cable-i}} = R_{\text{spec-cable-i}} \cdot L_{\text{cable-i}} \]  \( \text{(5)} \)

where \( R_{\text{spec-cable-i}} \) is value of specific resistance of cable \( i \) (\( \Omega/km \)) and \( L_{\text{cable-i}} \) - length of cable section \( i \).

From principal diagram of power plant shown in Figure 1 it can be seen that on individual low voltage cable maximum expected active power through cable (section) is maximum power of individual inverter (first cable section to first switching board) or sum of maximum power of several inverters connected to first switching board (on second section of cable from first switching board to main switching board). Formula is:

\[ P_{\text{cable-i-nom}} = \sum_{i=1}^{n} P_{\text{inv-i-nom}} \]  \( \text{(6)} \)

in which \( n \) is number of inverters current of which can flow through cable section \( i \).

Total losses of active power on low voltage cables (\( \Delta P_{\text{cable-LV}} \)) equals to the sum of losses on all individual cable sections:

\[ \Delta P_{\text{cable-LV}} = \sum_{i=1}^{n} \Delta P_{\text{cable-i}} \]  \( \text{(7)} \)
where \( i = 1 \) to \( n \) are low voltage cables in power plant.

C. Transformer

Power losses in transformer occur due to transformer core magnetization (losses in iron) and dissipation on resistance of transformer windings (winding losses). Core magnetization losses depend on voltage and do not change at different loads, while winding losses depend on transformer load in operation, and are proportional to square of current flowing through transformer windings.

Stated above is applicable to losses in transformer in general and is also applicable to active power losses. It is described by following relation:

\[
\Delta P_{tr} = \Delta P_{nc} + P_0 = k^2 \cdot P_{nc} + P_0
\]  \((8)\)

where \( \Delta P_{tr} \) is active power losses in transformer, \( \Delta P_{nc} \) is winding losses, \( P_0 \) is (rated) active power losses due to core magnetization (open circuit losses), \( P_{nc} \) is rated losses of active power in windings (short circuit losses) and \( k \) is portion of momentary active power in maximum total possible active power (rated transformer power).

Rated open circuit losses \( (P_0) \) and rated short circuit losses \( (P_{nc}) \) are parameters which are usually defined by transformer manufacturer and as such are known input data for calculation of other values (of power losses).

D. Medium voltage cable

Value of losses of active power on medium voltage cable can also be calculated from relation \((4)\). As there is only one MV cable, the relation becomes:

\[
\Delta P_{cab-MV} = \sqrt{3} \cdot R_{cab-MV} \cdot I_{cab-MV}^2 = \sqrt{3} \cdot R_{cab-MV} \cdot \left( k \cdot \frac{P_{cab-MV-nom}}{\sqrt{3} \cdot V} \right)^2
\]

\((9)\)

where \( \Delta P_{cab-MV} \) is active power losses on cable, \( R_{cab-MV} \) is value of MV cable resistance, \( I_{cab-MV} \) is current through MV cable, \( V \) is phase voltage (MV) and \( P_{cab-MV-nom} \) is maximum active power transferring through MV cable.

E. Auxiliary (house) consumption

If there is any active power consumption within the power plant connected prior to the point of common coupling with the grid (either to LV or MV level), total active power of these consumers is considered as loss of power of the power plant. As this power \( (P_{au}) \) is characteristic of consumption, it is treated as defined input parameter to total sum when calculating the total active power of the power plant. Anyway, it should be noted that this power is not constant.

F. Total active power of the power plant

To calculate the total active power of the power plant it is necessary to summarize all previously described power and losses on individual elements:

\[
P_{tot} = P_{inv-tot} - \Delta P_{cab-LV} - \Delta P_{tr} - \Delta P_{cab-MV} - P_{hc}
\]

\((10)\)

where \( P_{tot} \) is total power plant active power in point of connection to operator MV grid in particular moment and \( P_{hc} \) is active power of power plant house consumption.

VI. REACTIVE POWER (Q) OF POWER PLANT AT PCC

A. Inverters

Considering possibility of generating reactive power, there is a wide diversity among different products (inverters). The best inverters are capable to generate any reactive power (Figure 2), in accordance with setting requirements for automatic power factor regulation. But, as is emphasized few times already, power plant investors/owners want to economically optimize their production, which leads to setting of power factor to 1.

With some inverters there is a problem with power factor regulation when there is no generation power on the DC side. Following it, there is no current on the AC output side generated, and no regulation of the power factor. The output L-C filter is of capacitive character at nominal frequency, and during these periods is dominative element, which makes these inverters generators of pure reactive power in values of few percent of nominal inverter power [6]. At photovoltaic power plants at which panels are connected through inverters without galvanic isolation of DC and AC side, parasitic impedances of PV panel cells are transferred to AC side [5]. Depending on the size of PV field and the installation, this capacitive power can be significant and in values of few percent of the power plant nominal power in case of single-phase inverters without galvanic isolation.

1) Inverter reactive power with power factor set

Inverters, as power electronic devices, have flexible possibilities for active and reactive power generation. Depending on power factor set, reactive power generated by inverter changes. Value of inverter reactive power is:

\[
Q_{inv-i} = S_{inv-i} \cdot \sin \varphi_{inv-i}
\]

\((11)\)

where \( Q_{inv-i} \) is reactive power of individual inverter, \( S_{inv-i} \) is apparent power of individual inverter, \( \sin \varphi_{inv-i} \) is sinus of power factor angle of individual inverter.

Therefore, total influence of all inverters to reactive power plant power equals to sum of momentary reactive powers of all individual inverters:

\[
Q_{inv-\Sigma} = \sum_{i=1}^{n} Q_{inv-i}
\]

\((12)\)

where \( Q_{inv-\Sigma} \) is sum of generated reactive power of all inverters in defined moment.

2) Capacitive power of inverters due to parasitic capacitances at DC side

With almost all single-phase inverters without galvanic isolation (without integrated transformer), half amplitude of grid voltage (115 V) is passing to DC side and coming to photovoltaic (PV) cells. In three phase inverters this phenomenon is significantly suppressed [6]. With inverters with integrated transformers for galvanic isolation transferred voltage oscillates with amplitude of just few Volts (2 V), changing constantly the charge of parasitic capacitances of PV cells. In this case resultant capacitive power is usually of neglected value.
Capacitive current due to parasitic capacitances of field of PV modules equals to [6]:

\[
I_{\text{par}} = C_{ PV} \cdot \frac{\Delta Q_{ PV}}{\Delta t} = C_{ PV} \cdot 2 \cdot \pi \cdot f \cdot V_{\text{par}}
\]  

(13)

where \( C_{ PV} \) is parasitic capacitance of PV modules, \( f \) is grid frequency (50 Hz) and \( V_{\text{par}} \) is value of transferred (parasitic) AC voltage to DC side (ripple voltage).

Capacitance of PV modules can be assessed from:

\[
C_{ PV} = \varepsilon_0 \cdot \varepsilon_r ^* \cdot \frac{A_{ PV}}{d_{ PV}}
\]  

(14)

where \( \varepsilon_0 = 8.85 \cdot 10^{-12} \) As/Vm is vacuum permittivity constant, \( \varepsilon_r ^* \) is (5-10) is relative glass permittivity constant (glass from which PV cells are made of), \( A_{ PV} \) is photovoltaic modules surface area and \( d_{ PV} \) is distance between condenser surfaces (thickness of PV panels).

Total capacitive reactive power of all inverters due to described phenomena is:

\[
Q_{\text{m-par}} = 3 \cdot V \cdot I_{\text{m-par}} = 6 \pi \cdot V \cdot \varepsilon_0 ^* \cdot \varepsilon_r ^* \cdot \frac{A_{ PV}}{d_{ PV}} \cdot f \cdot V_{\text{par}}
\]  

(15)

where \( Q_{\text{m-par}} \) is total capacitive power of all inverters together due to influence of parasitic capacitances of the field of photovoltaic modules and \( V \) is phase voltage.

3) Total reactive power produced by inverters

Total inverter reactive power equals to sum of set value of reactive power and parasitic capacitive power:

\[
Q_{\text{inv-to}} = Q_{\text{inv}} + Q_{\text{m-par}}
\]  

(16)

where \( Q_{\text{inv-to}} \) is total reactive power of all inverters.

When summing up the reactive powers it is necessary to keep in mind reactive power character. Inductive reactive powers are entered to calculation with negative sign and capacitive powers with positive.

Equation (16) is not correct for inverter "stand by" periods, when there is no input power and inverter is "dead", and when output L-C filter, which is of capacitive character at nominal frequency of AC grid, generates capacitive reactive power.

B. Low voltage cables

Low voltage cables connect inverters to "unit" transformer, through few summation points (switching boards). When not loaded they are of mild capacitive characters. As this capacitive power is dependent also on voltage (which is on LV level relatively small), only in case of very large lengths (large power plant surfaces) this power can have significant values. Inductive component of reactive power is larger as cable load is getting larger.

Value of cable reactive power can be assessed from following equation, using cable catalogue data:

\[
Q_{\text{par}} = 3 \cdot \frac{V_{L-C} ^2}{X_{L-C}} - 3 \cdot I_{L-C} ^2 \cdot X_{L-C} = 6 \cdot \pi \cdot f \cdot V_{L-C} ^2 \cdot C_{ \text{par}} - 6 \cdot \pi \cdot f \cdot \frac{S_{\text{par}} ^2}{V_{L-C} ^2} \cdot L_{\text{par}} - I_{\text{par}} ^2 \cdot X_{\text{par}}
\]  

(17a)

where \( Q_{\text{par}} \) is reactive power of cable \( i \), \( X_{\text{par}} \) is capacitive reactance of cable \( i \), \( X_{L-C} \) is inductive reactance of cable \( i \), \( L_{\text{par}} \) is current through cable \( i \), \( C_{ \text{par}} \) is specific capacitance of cable \( i \), \( L_{\text{par}} \) is specific inductance of cable \( i \), \( S_{\text{par}} \) is length of cable \( i \) and \( S_{\text{par}} \) is power flowing through cable \( i \).

For \( S_{\text{par}} \) the following relation is applicable:

\[
S_{\text{par}} = k \cdot S_{\text{nom-cabl}}
\]  

(18)

where \( k \) is cable load factor - portion of power flowing in specific moment in nominal power (maximum power through cable when there is maximum generation from inverters) and \( S_{\text{nom-cabl}} \) is nominal power (maximum power through cable when there is maximum generation from inverters) of cable \( i \).

Total reactive power on low voltage cables is:

\[
Q_{\text{L-V}} = \sum_{i=1}^{n} Q_{\text{par}}
\]  

(19)

where \( i = 1 \) to \( n \) are all low voltage cable in power plant.

C. Transformer

Transformers need reactive power for core magnetizing, therefore, when not loaded, transformers are of inductive character. As load of transformer gets larger, inductive reactive power also gets larger, due to inductivity of transformer windings. Value of this reactive power can be assessed by following equation:

\[
Q = Q_b + Q_L + Q_{\text{sc}} + k \cdot Q_c = \sqrt{P_0 ^2 + \left( S_{\text{sc}} \cdot \varepsilon_0 ^* \cdot \varepsilon_r ^* \cdot \frac{A_{ \text{sc}}} {d_{ \text{sc}}} \right)^2} + k \cdot \sqrt{S_{\text{sc}} ^2 \cdot \varepsilon_0 ^* \cdot \varepsilon_r ^* \cdot \frac{A_{ \text{sc}}} {d_{ \text{sc}}} ^2 + P_0 ^2}
\]  

(20)

where \( Q_b \) is transformer reactive power, \( Q_b \) is reactive power of non-loaded transformer, \( Q_{\text{sc}} \) is reactive power dependable on transformer load, \( k \) is transformer load factor - portion of load power in specific moment in transformer nominal power, \( S_{\text{sc}} \) is transformer nominal power, \( \varepsilon_0 ^* \) is short circuit current (%), \( \varepsilon_0 ^* \) is short circuit voltage (%), \( P_0 \) is (nominal) losses of active power due to core magnetizing (active power losses in open circuit) and \( P_{\text{sc}} \) is nominal losses of active power in windings (active power losses in open circuit). Data on \( \varepsilon_0 ^* \), \( \varepsilon_0 ^* \) and \( P_{\text{sc}} \) are all declared by manufacturer.

D. Transformer inductivity compensation

Allowing the possibility that the compensation batteries can also be installed in LV switchboards with aim to compensate for transformer inductive losses, they must be considered. In practice they can have one of type power levels, according to nominal power of transformer. Installation of batteries is usually not useful, due to reason that during power plant design the calculation of total power plant reactive power is not considered. Resulting total reactive power can be capacitive and in that case these compensation batteries will, with its capacitive power (\( Q_{\text{batt}} \)), only make the situation worse. The relation for battery power is:
where \( Q_{\text{batt}} \) is compensation battery reactive power, \( X_{C-\text{batt}} \) is reactance of capacitor and \( C_{\text{batt}} \) is capacitor capacity.

E. Medium voltage cable

Medium voltage cables connect power plant with the point of connection to grid system. They are of distinct capacitive character and in cases of larger lengths (few hundred meters) they become element with major influence on reactive power at point of connection. Values can also be calculated by modified equation (17a and 17b),

\[
Q_{\text{cab-MV}} = 6 \cdot \pi \cdot f \cdot U_{\text{MV}}^2 \cdot C_{\text{cab-MV}} - 6 \cdot \pi \cdot f \cdot \frac{S_{\text{inv}}}{U_{\text{MV}}} \cdot L_{\text{cab-MV}} \cdot l_{\text{cab-MV}} \tag{22}
\]

where \( Q_{\text{cab-MV}} \) is cable reactive power, \( C_{\text{cab-MV}} \) is specific capacitance, \( L_{\text{cab-MV}} \) is specific inductance, \( L_{\text{cab-MV}} \) is cable length and \( S_{\text{inv}} \) is power flowing through cable.

F. Auxiliary (house) consumption

Same as with active power, if there is any reactive auxiliary power consumption within the power plant total reactive power of these consumers should be considered.

G. Total reactive power of the power plant

To calculate the total reactive power of the power plant it is necessary to summarize all previously described element powers with correct sign:

\[
Q_{\text{tot}} = Q_{\text{inv-MV}} + Q_{\text{batt}} - Q_{\text{cab-MV}} + Q_{\text{aux}} \tag{23}
\]

where \( Q_{\text{tot}} \) is total reactive power of the power plant in point of connection to MV grid in particular moment and \( Q_{\text{inv-MV}} \) is reactive power of power plant house consumption.

According to previous equations defined for reactive powers, the following dependencies which influence the value of total reactive power at PCC can be deduced: inductive part of reactive power gets larger with the rise of momentary power, i.e. generation of power plant, and capacitive part is larger when the grid voltage gets larger. Also, considering that allowed (possible) changes of frequency are very small, it can be assumed that frequency is constant.

VII. POWER PLANT OPERATION CHART IN P-Q DIAGRAM

When the above equations are entered to (10) and to (23), and with known values which are equipment characteristics, relations for \( P_{\text{tot}} \) and \( Q_{\text{tot}} \) dependable on only two changing variables: voltage and momentary generation power (generated from PV cells and transferred to grid through inverters), can be determined. As limit values of these two variables are also known, formulas for curves of maximum and minimum values for \( P_{\text{tot}} \) and \( Q_{\text{tot}} \) can be calculated when maximum and minimum values of changing variables are entered to equations. Area in P-Q diagram bordered by calculated curves is area of possible power plant operation points. This area represents operation chart of photovoltaic power plant connected to MV grid, at PCC [7].

Minimum and maximum values for these two variables are known: possible (allowed) range of voltage value in LV grid is from 0,9 \( U_{n} \) to 1,1 \( U_{n} \). Generation power from technological side of power plant can vary from 0 up to maximum nominal power of all inverters.

Previously stated is applied to actual case study PVP, for which P-Q diagram of possible operation points is constructed following described procedure. Actual measurement readings are used for model verifications.

A. Theoretical constraints versus prescribed constraints and constraints due to settings (of power factor)

Prior to constructing operation chart of this type of power plant it is necessary to have a look on power plant (inverters) power factor. The reason for this is large influence which it has on operation point of power plant, as can be seen from relations (1) and (11).

Power factor can be assessed from three perspectives. The first one is theoretical possibility for output power factor of inverter(s) itself. Inverters are advanced power electronic devices and as such can have large options of transferring input power to output power with power factor in wide range. Manufacturers declare the capabilities for their inverter and from this aspect of view restrictions are dependable only on technical capabilities of inverters.

Despite the inverter capabilities, system operator rules [8] define that the additional (over the agreed level) produced or consumed reactive energy of producer is surplus which will be charged to him. Overproduced reactive energy is for power factor less than 0,95 so this value can be assumed to be the lowest setting in inverters.

And as third aspect of view, considering the fact that owner of the distributed source gets revenue based only on active power produced, it can be assumed that economy logic will have effect that inverters power factor values are set to 1, to produce active power only.

Following all three previously stated facts, for developing the operation chart in this study, theoretical capabilities of inverters will not be considered. Realistic P-Q diagram which includes all expected operation points will be constructed regarding inverter power factor set, with emphasis on power factor 1, and also with reflection to the grid operator limit for the penalization power factor, i.e. power factor set to 0,95.

VIII. APPLICATION OF PROPOSED MODEL OF OPERATION CHART CONSTRUCTION TO CASE STUDY POWER PLANT

Solar PVP Kanfanar, located in Istra, Croatia, rated power of 1MW (999 kW installed PV panel power, 912 kW installed inverter power), after its commissioning (March 2013) has been the largest PV plant in Croatia and first PV plant to be connected to MV grid of the electrical system operator HEP-ODS. Since then few similar power plants have been connected [1].

This power plant served as specific case study for the type of power plants that are subject of this research, photovoltaic plant with multiple inverter units connected to medium
voltage grid. Principle diagram is shown on Figure 1. Power plant elements data [9] are used for calculations made in the following sections.

A. Calculative assessment and analysis of active power

Using equations for generation and losses of active power for individual elements of PVP Kanfanar, influence of all elements to total active power is assessed. The values are given herewith.

Maximum active power of inverters with set power factor \( \cos \phi = 1 \) is 912 kW. During night work regime, inverters consume 1.72 W each, so minimum active power of all inverters is -0.13 kW during night.

Calculated maximum active power losses on all LV cables together are 0.79 kW, which equals to 0.087 %.

Losses of active power on power plant unit transformer are are from 1.75 kW in open circuit up to 12.97 kW at maximum transformer load. Portion of these losses is from 0.19 % to 1.4 % of maximum rated power.

Calculated maximum active power losses on MV cable are 0.2 W, which can be neglected.

Total rated power of auxiliary consumption is around 1 kW and is not constant.

Total calculated active power of PVP Kanfanar at PCC is changing from minimum -2.88 kW (when inverters do not produce power) to maximum 898.04 kW. Active power relative range is from -0.31 % to 98.47 % of total inverter rated power.

B. Calculative assessment and analysis of reactive power

There is no reactive power from inverters when power factor is set to 1. Contribution due to parasitic capacitances of PV modules transferred to AC side equals to 13.30 kVA\(_{\text{cap}}\) (1.46 % in relation to rated plant power). There has been no known data on output filter capacitance (during "stand by" periods of inverter work output filter, which is at nominal frequency of capacitive character, dominates). It is assumed that value of maximum contribution for all inverters is approx. 2 % of inverter power. Maximum value for all inverters is 18.24 kVA\(_{\text{cap}}\).

Capacitive character is dominating with calculated total reactive power on LV cables practically constant for any inverter generation power with value of 30 VA\(_{\text{cap}}\), which is only 0.0033 % in rated power of the power plant.

Contribution of unit transformer to inductive reactive power is 7.81 kVA\(_{\text{ind}}\) (0.8 %) when there is no production up to 56.70 kVA\(_{\text{ind}}\) (6.2 %) at maximum plant power.

Contribution of compensation battery is 60 kVA\(_{\text{cap}}\). It is not included to calculation of total reactive power as battery was disconnected after commissioning of the plant.

On MV cable there is practically constant capacitive reactive power of 9.81 kVA\(_{\text{cap}}\) (1.1 % relatively).

Resulting total reactive power is changing from capacitive 15.34 kVA\(_{\text{cap}}\) during night work to inductive 33.56 kVA\(_{\text{ind}}\) at maximum possible power output. Relative range is from -1.68 % to 3.68 % of rated power.

C. Operation chart construction in P-Q diagram

Herewith equations given in chapters 5 and 6 are used for construction of (border) curves in P-Q diagram, i.e. for development of operation chart for the PVP with multiple inverter units connected to MV grid, all based on case study power plant PVP Kanfanar. The process of construction of operation chart is explained in detail.

As first iteration, operation chart for theoretical capabilities of power plant is drawn. It is defined by equipment (inverter) constraints and by characteristics of other elements which form power plant.

Inverters in PVP Kanfanar have capabilities of setting the power factor value to \( \cos \phi = 0.75 \) ind./cap. which is considered for theoretical operation chart construction. Relations (10) for total active power and (23) for total reactive power are used, and all other relations for individual element contributions are entered to these.

The curve of "minimum active power" (curve \( p_{\text{min}} \) on Figure 3) is curve of all pairs of values \( (P_{\text{tot}}, Q_{\text{tot}}) \) with condition that inverters do not deliver energy to the grid \( (P_{\text{inv}} = 0 = \text{const.}) \). All constant values for equipment and individual elements are entered to relations, and frequency is assumed to be constant as its small changes do not affect total power calculation. Changing variable is only voltage (but voltage range is constraint from operator side [10]), and curve goes from starting point for \( U = 0.9 \cdot U_n \) to final point for \( U = 1.1 \cdot U_n \).

The curve of "maximum reactive power" (or maximum capacitive reactive power, curve \( q_{\text{max}} \) on Figure 3) connects all points which are pairs of values \( (P_{\text{tot}}, Q_{\text{tot}}) \) under condition that grid voltage is maximum allowed \( (U = 1.1 \cdot U_n = \text{const.}) \) and that the power factor set in inverters is minimum capacitive (in PVP Kanfanar it is \( \cos \phi = 0.75 \text{cap} \)). Changing variable is inverter power, from \( S_{\text{inv-cap}} = 0 \) to \( S_{\text{inv-cap}} = S_{\text{inv-cap-max}} = 912 \text{kVA} \). Curve goes from starting point (no generation from inverters) to final point (maximum total apparent power of inverters).

The curve of "maximum active power" (curve \( p_{\text{max}} \) on Figure 3) connects all points which are pairs of values \( (P_{\text{tot}}, Q_{\text{tot}}) \) under condition that inverters deliver maximum active power with all possible power factor settings \( (\cos \phi = 0.75 \text{cap} - 0.75 \text{ind}) \). Other condition is that grid voltage is maximal \( (U = 1.1 \cdot U_n = \text{const.}) \) when inverters operate in capacitive regime, and is minimal \( (U = 0.9 \cdot U_n = \text{const.}) \) when inverters operate in inductive regime. Curve goes from starting point for minimum possible capacitive power factor to final point for minimum possible inductive power factor of inverters.

The curve of "minimum reactive power" (or maximum inductive reactive power, curve \( q_{\text{min}} \) on Figure 3) connects all points which are pairs of values \( (P_{\text{tot}}, Q_{\text{tot}}) \) under condition that grid voltage is minimum allowed \( (U = 0.9 \cdot U_n = \text{const.}) \) and that the power factor set in inverters is minimum inductive (in study case of PVP Kanfanar it is \( \cos \phi = 0.75 \text{ind} \)). Changing variable is inverter power, from \( S_{\text{inv-cap}} = S_{\text{inv-cap-max}} = 912 \text{kVA} \) to \( S_{\text{inv-cap}} = 0 \). Curve goes from starting point (maximum apparent power of inverters) to final point (no inverter generation).
P-Q diagram (operation chart) with described border curves is drawn on Figure 3. Figure shows theoretical operation chart for case study plant PVP Kanfanar. Actually, in real operation of this power plant (this type of power plants), once set power factor is constant and does not change. It is pragmatically to accept this fact and try to construct operation chart which would be more correct, and would not encompass all theoretically possible operation points, but operation point which are realistic in real-life operation. To construct such operation chart, power factor for inverters is considered constant, in case of PVP Kanfanar being set to \( \cos \phi = 1 \). Such power factor is expected for all power plants of this type, as in such way also the potential revenue is maximized, which is main consideration for power plant investors.

Figure 4 shows (constructed from calculations) realistic operation chart for PVP Kanfanar magnified reactive power axis in comparison to Figure 3. Inverters power factor setting of \( \cos \phi = 1 \) causes dislocation of "maximum reactive power" and "minimum reactive power" curves compared to theoretically possible.

It can be concluded, that during night operation capacitive reactive power dominates as influence of output L-C filter capacitive power and capacitive power on MV cable, while inverters are in "stand-by" mode. After the sunrise, inverters turn on, output filter does not generate capacitive power, active power of the power plant is rising followed by the rise of inductive power (greatest influence from transformer) which moves reactive power from capacitive to inductive area, at middle of the power plant rated power. At maximum plant generation the inductive power component is biggest.

IX. MEASUREMENTS TAKEN ON CASE STUDY POWER PLANT

Correctness of this modeling of operation chart is compared to measurements in real operation. During the PVP Kanfanar test operation certain measurements were taken which are used for this study [11]. Total period of measurements was 11 days, from 15.2.2013. till 26.2.2013. Curves of active and reactive power for this period are given on Figure 5, showing power plant active power (P) and reactive power (Q), and are drawn from 10-minute measurement values of average power at PCC to MV grid. In graphical showing, positive active power means delivering energy to grid, positive reactive power means capacitive power of power plant. Measurements were taken on 20 kV bus at connection point for PVP Kanfanar, by measurement device through measuring core of voltage transformer and secondary protection core of current transformer which could have entered certain error to taken measurements. On graph shown, the difference in daily power generation diagrams of PV plant can easily be seen, i.e. dependence on weather conditions.

When all measured operating points (pairs of values \( P_{tot}, Q_{tot} \)) of the power plant generation graph from Figure 5 are shown in coordinate system with P and Q axis (P-Q diagram), the outcome is P-Q diagram with drawn trajectory of operating points for PVP Kanfanar for measurement period, as shown on Figure 6.

P-Q diagram with operation point trajectory obtained from case study measurements can be compared to power plant operation chart constructed from calculations, shown on previous figures. Figure 7 shows overlapped power plant operation chart from Figure 4 with diagram of measured points in measurement period from Figure 6.
Comparison of overlapped diagrams shows similarity, but there is dislocation of theoretical operation chart from measurement values, in middle part of constructed curves. Inductive power is more significant in this part of curves.

Second conclusion is related to inverter power factor setting, which, although deemed "fixed", is not such firm, as output power factor is regulated within inverter by closed loop regulation with certain sensitivity, so it can be assumed that set power factor has certain deviation range. Considering that, allowance for power factor deviation (for set value of $\cos\phi=1$) in range of $\cos\phi=0,9995\text{cap}$ to $\cos\phi=0,9995\text{ind}$ (which is realistic expectation due to regulation) is considered. Inductive power factor moves "minimum reactive power" curve more to inductive side. Also, considered is the first conclusion related to non-existence of parasitic capacitance in "no generation" period, and all other assumption are kept as previously described. Figure 8 shows constructed corrected operation chart overlapped with measured trajectory of operation point movement during measurement period.

It can be noticed that on larger power generation of power plant measured operation points are further from border values regime to active regime, transferring power from DC side to AC grid. In the moment when there is power available on inverter input, inverter turns on and in this period output L-C filter does not generate reactive power to grid which results with step change to lower capacitive power [5]. Only with next stage, delivering of power to AC grid, there comes also the effect of delivering additional capacitive power due to explained transmission of parasitic PV panel capacitances to AC side. Unsynchronized switching of inverters (large number of 76 inverters in studied case) in a period of several minutes, makes angle rise of the trajectory to the operating point with larger capacitive power, when all inverters are turned on to normal regime. When constructing the operation chart this phenomenon can be encompassed by extension of the "minimum active power" curve to inductive area, i.e. by compensating the reactive power for value of capacitive reactive power due to parasitic capacitances for "no generation" period.
from which it can be concluded that self-regulation of inverter power factor is more precise for larger power values. On Figure 8 also curve for "expected" trajectory of power plant operation points is drawn, for fixed inverter power factor $\cos\phi = 1$ and for nominal voltage value. Curve is marked with "$\text{pf}_1, U_{n}$". It can be noticed that operation points do not follow the curves (second order curves), their rise trend is more linear. Reasons can be the influence of the power plant itself to voltage profile at PCC. Power delivered to feeder is rising the voltage value (or lowering the feeder voltage drop) on this part of grid. Higher voltage has influence on rise of capacitive component of reactive power of power plant (of MV cable majorly) and trajectory curve move from expected second order curve (which would be for constant voltage) to close to linear dependency.

XI. CONCLUSION

Following the above analysis, it can be concluded that operation chart constructed from given calculations, with noted assumptions considered, can be modelled in a way it realistically shows area of possible operation points for multi-inverter PVP connected to MV grid.

REFERENCES

[8] Croatian energy regulation agency: "General conditions for grid operation and electrical energy supply" (NN 85/2015)