Conference contribution :
Todeschini, G. (2017). *Control and derating of a PV inverter for harmonic compensation in a smart distribution system.* Power & Energy Society General Meeting, 2017 IEEE, (pp. 1-5). Chicago, IL USA: Energizing a more secure, resilient, and adaptable grid.
http://dx.doi.org/10.1109/PESGM.2017.8274607

Control and Derating of a PV Inverter for Harmonic Compensation in a Smart Distribution System

Grazia Todeschini, *Senior Member, IEEE*
Swansea University, College of Engineering
Swansea, UK
grazia.todeschini@swansea.ac.uk

***Abstract*— Due to the high number of photovoltaic (PV) inverters installed, in some regions of the UK the power generated under peak conditions exceeds the transmission system capacity limits. With the aim to mitigate this condition and operate the grid within its design limits, utilities curtail PV output power, thus causing financial loss for the PV system owners and limiting the use of the installed components. The control system proposed in this paper allows using the PV inverter as an Active Filter (AF), when the output power is curtailed, thus improving the system power quality and exploiting the installed MVA. A novel contribution is the description of a harmonic derating coefficient which limits harmonic current injection based on the fundamental current generated by the inverter. The proposed application fits within the scope of the smart grid, where multi-functional inverters can be controlled by utilities to improve grid operating conditions.**

***Index Terms*—Active Filter, Derating, dq Transformation, Power Quality, Smart Grid**

I. Introduction

The number of distributed resources (DRs) installed worldwide has been increasing rapidly due to a number favorable conditions, including decreasing cost of these technologies, incentives from governments, and retirement of coal plants. A large number of DRs installed in a relatively small geographical area may interfere with the daily operation of the local power system, which typically is designed under the assumptions of centralized power generation and unidirectional power flow. This problem is well-known and the impact of DRs on power system operation has been addressed in many publications, including [1] and [2].

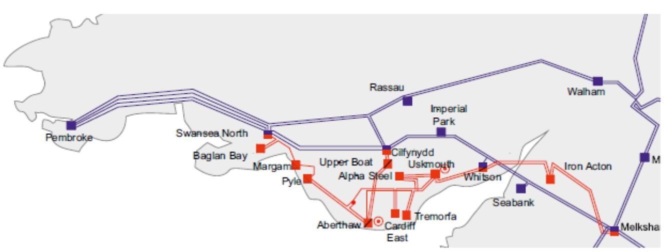

Figure 1: Transmission System Configuration in South Wales [4]

In South Wales, a high number of PV inverters has been installed in the last decade. The high penetration of DRs is a relatively small area resulted in concerns from the local utility in terms of voltage profile, thermal limits, and fault levels [3]. The transmission system connecting South Wales to the rest of the UK is mostly radial, as shown in Figure 1, and therefore there are only a few routes to dispatch the power generated by the local DRs [4]. As a result of the increased number of PV installations in this area, in June 2016 the export capacity limits for the transmission system in South Wales have been exceeded.

The dispatch of solar energy is further limited by the fact that in the UK, load profiles and generation profiles are shifted. Figure 2 shows typical seasonal load levels for 2010, and indicated that the peak load takes place in the winter, while the summer load is on average 30% lower.

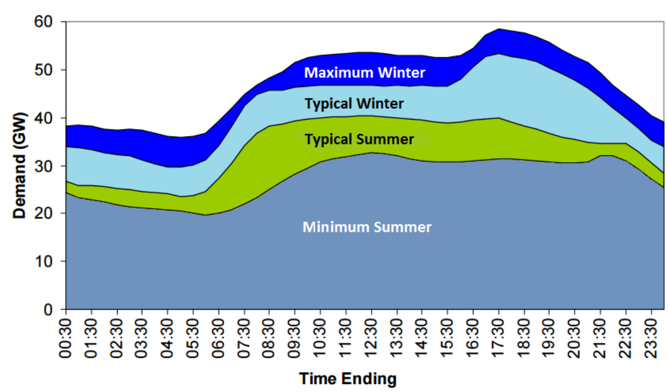

Figure 2: Typical seasonal loads in the UK [4]

On the contrary, PV generation is at peak in the summer and at minimum in the winter. While in other countries the use of ac conditioners in the summer helps matching generation and demand, in most areas of the UK the summer peak generation from PV panels cannot be dispatched. Since at the moment a long-term energy storage system is not viable, the only solution to match generation levels and load levels is to curtail PV power output. Several UK utilities have developed alternative connections options, with different degrees of complexity, to allow installation of new DRs, while meeting the operating constraints. In some cases, the PV connection is 'timed', thus meaning that the generation is curtailed at specific hours of the day. A more sophisticated interconnection method is named 'Active Network Management', which consists in monitoring continuously the levels of generation and demand, and adjusting the PV power output based on the system conditions [6]. Obviously, the perspective of curtailment may discourage DR developers, as the reduced power out results in a loss of revenue.

From the point of view of performance, the control of the last generations of PV inverters has become quite sophisticated. In addition to algorithms which allow maximizing power generation, several ancillary services may be provided, such as frequency control, voltage regulation, spinning reserve, black start capability and grid loss compensation [7]. One of these applications consists in using the PV inverter as active filter (AF). The concept of AF has been proposed a few decades ago [8] and consists in using an inverter to absorb harmonic current components already present in the power system. In spite of being very effective and precise, AFs are seldom used in the practice due to the cost of this technology when compared to passive filters. A second drawback of AFs is that their operation requires a very accurate measurement of load and/or grid harmonic currents, which is not always possible due to limitations in the instrumentation accuracy and availability of meters [9].

More recently, there has been a renewed interest in the use of AFs, given that this feature can be provided as 'ancillary service', and the harmonic current levels in the power system have been increasing [10], [11]. The use of PV inverters as AFs is described in several publications, including [12]-[14]. The majority of algorithms proposed to achieve AF operation do not address the following concern: when harmonic currents are generated in addition to the fundamental component, there is a risk of exceeding the current rating of the power electronic switches. To ensure that current ratings are not exceeded, an algorithm needs to be added to the control, to either curtail the fundamental power output or to limit the harmonic currents generated by the inverter when current rating is exceeded. An algorithm which provides these functionalities for wind power generators is described in [15].

The control strategy presented in this paper is intended to conciliate the concerns and limitations described above:

- From the point of view of the utilities: when the power generated by DRs exceeds the capacity limits, the inverter power output is curtailed. Additionally, the high number of DRs results in increasing harmonic levels.
- From the point of view of the inverter manufacturers, curtailment results in loss of revenue and therefore may discourage new installations
- From the point of view of the inverter control, AF operation may be implemented simultaneously to power generation, but an algorithm needs to be included to verify that the inverter current rating is not exceeded

The control strategy described in this paper to solve the issues highlighted above is based on these assumptions:

- The PV inverter is operated simultaneously for power generation and AF operation;
- Power generation is given priority in the control, while the utility may curtail the output power depending on the system conditions.
- The rms and peak current at the inverter terminals are continuously monitored and a 'harmonic derating coefficient' is introduced to limit harmonic current injection when the inverter operates close to full rating.

II. Control System

The system under study is shown in Figure 3, and consists of a Non-Linear Load (NLL) and a PV panel connected to the grid by means of a power converter and a transformer. The distribution system is illustrated by means of a Thevenin equivalent (voltage source and series impedance).

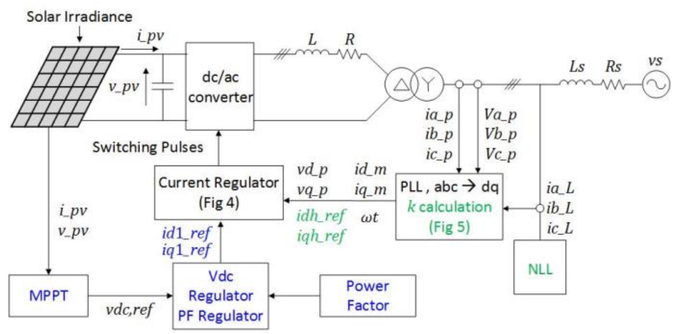

Figure 3: Single-phase diagram of the PV system, Non-linear Load (NLL) and of the main control blocks

The control system for the PV inverter is obtained as the superposition of two algorithms, dedicated to the regulation of fundamental current and of harmonic currents, respectively. The main components of the proposed control are shown in Figure 3, where the blue color is used to indicate the terms dedicated to fundamental current regulation, and the green color is used to indicate the terms dedicated to harmonic current regulation. The notation used in Figure 3 and in the rest of the paper is as follows:

- *_pv*: quantity measured at PV panel output
- *_p*: quantity measured at transformer primary side
- *_l*: quantity measured at load terminals
- *_ref*: reference quantity
- *_err*: error term
- 1: fundamental component
- *h*: harmonic component

A. Fundamental Current Control(blue path)

The fundamental current control is based on the use of algorithms which are standard for PV inverters operation. Therefore, only aconceptual overview is provided in this paper, while more details can be found in [12]-[14]:

- A Phase-Lock Loop (PLL) calculates the system angular frequency ωt from the voltage measurements. The angular frequency ωt is used as one of the inputs for the algorithm which performs the *dq* transformation [12]-[15]. The *dq* transformation is used to convert voltage and currents measurements into the *dq* domain [8].

- A MPPT algorithm (based on the 'perturb and observe' approach) is included to capture the maximum power based on the radiation level [12]. The output of the MPPT algorithm is the voltage *vdc_ref*.
- A Vdc regulator is used to calculate the *d*-axis fundamental reference current (*id*1*_ref*). The *q*-axis fundamental reference current (*iq*1*_ref*) is obtained from the power factor setting. In most cases, the power factor is unity and therefore the current *iq*1*_ref* is zero, but in theory the power factor can be set to any value between 0 and 1, and can be dynamically modified.
- A current regulator is used to generate the switching pulses, from the current measured at the transformer primary side (*id_m* and *iq_m)* and the reference currents (*id_ref* and *iq_ref),* as shown in Figure 4. The calculation of the reference currents is explained in the next paragraph. The input to the PI controller is the current error, obtained as difference between measured currents and reference currents. A feedforward term is included to increase control accuracy [16], but is not shown in the diagram to keep the figure clear. The parameters of PI controller are dependent on the frequency of the harmonic currents to be compensated. For typical distribution systems, the frequency range of interest is between the 3rd and the 13th harmonic [1],[7],[17].
- A Pulse-Width-Modulation (PWM) algorithm is used to generate the switching pulses, based on the reference voltages in the phase domain (*va_ref*, *vb_ref* and *vc_ref*).

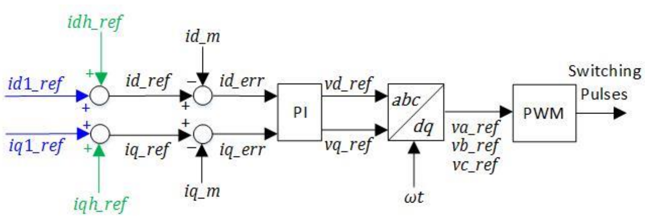

Figure 4: Current Regulator including the following control block: PI regulator, reverse *dq* transformation and PWM.

B. Reference Currents Calculation

The reference frame chosen for the *dq* transformation allows controlling the fundamental current components and harmonic current components separately. In this paper, the reference frame for the *dq* transformation rotates in synchronism with the fundamental voltage. As a result, the fundamental current components in the *dq* domain are either constants or slow-changing quantities, which can be easily filtered, while the harmonic current components are sinusoid.

As discussed in the previous section, the fundamental reference current components *id*1*_ref* and *iq*1*_ref* are obtained from irradiance and power factor setting. The harmonic reference current components *idh_ref* and *iqh_ref* are obtained from the current measurement at the NLL terminals, as shown in the top portion of Figure 5. The load currents in the *dq* domain (*idL* and *iqL)* are filtered to remove the dc current component, and then a -1 gain factor is applied because, under AF operation, the harmonic components injected by the inverter are opposite in phase to the harmonic currents injected by the load.

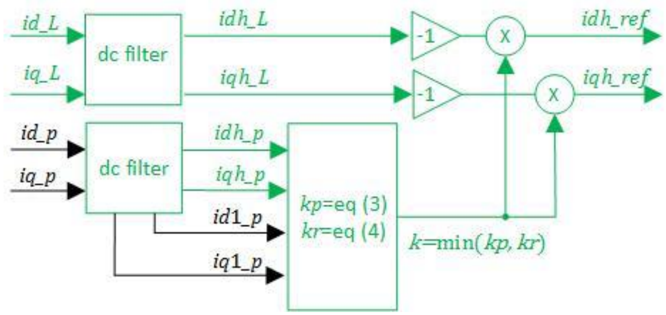

Figure 5: Reference harmonic currents calculation

A gain factor *k* is then applied to the harmonic reference currents, as discussed in the next section, thus obtaining the inverter harmonic reference currents.

The inverter reference currents in the *d* and the *q* domain are obtained by adding the fundamental and harmonic reference current components, as shown in Figure 5:

$$id\_ref = id1\_ref + idh\_ref$$

$$iq\_ref = iq1\_ref + iqh\_ref$$

C. Harmonic derating coefficient k

The main contribution of this paper is the description of an algorithm which allows limiting the amplitude of the harmonic currents injected by the inverter, to guarantee operation within design limits. The algorithm is based on these assumptions:

- The fundamental current is not limited by the inverter control. This assumption is motivated by two reasons: 1) power generation is a priority and is not limited to allow for harmonic currents injection, and 2) the proposed application is part of a smart grid, where the utility curtails power generation when required by the system conditions.

- The harmonic reference current is limited when the inverter output current peak value or rms value exceed the rated output current.

A coefficient *k*, with $0 \le k \le 1$, is introduced to express curtailment of the harmonic currents which are injected by the inverter. This coefficient is multiplied with the harmonic current reference components, as shown in Figure 5. When $k = 0$, no harmonic currents are injected; when $k = 1$, full harmonic current injection is allowed. The normalized expressions (where rated inverter current corresponds to 1) of peak inverter current and rms current are as follows:

$$id1 + iq1 + kp(idh + iqh) = 1 \quad (1)$$

$$Id1_{rms}^2 + Iq1_{rms}^2 + kr^2(Idh_{rms}^2 + Iqh_{rms}^2) = \frac{1}{2} \quad (2)$$

where the harmonic currents are weighted by the coefficients *kp* and *kr*, respectively.

The two equations can be solved for *kp* and *kr,* thus finding the solutions for the two coefficients:

$$kp = (1 - id1 - iq1)/(idh + iqh) \quad (3)$$

$$kr = (1/2 - Id1_{rms}^2 - Iq1_{rms}^2)/(Idh_{rms}^2 + Iqh_{rms}^2) \quad (4)$$

The coefficients kp and kr depends on four variables, but they can be plotted in a two-dimensional graph if two simplifications are applied:

- $iq1 = 0$ (unity power factor)
- $idh = iqh = ih$ (the amplitude of harmonic *d*-axis and *q*-axis harmonic components is the same. This condition is met for symmetrical systems)

Under the conditions above, (3) and (4) become, respectively:

$$kp = (1 - id1)/2ih \qquad (5)$$

$$kr = (1/2 - Id1_{rms}^2)/2Ih_{rms}^2 \qquad (6)$$

The variation of kp and kr as function of $id1$ and ih based on (5) and (6) are shown in Figure 6 and Figure 7, respectively.

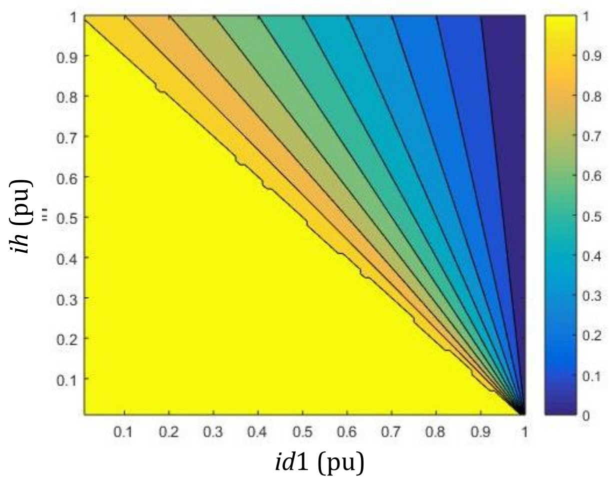

Figure 6: Variation of the coefficient *kp* according to (5)

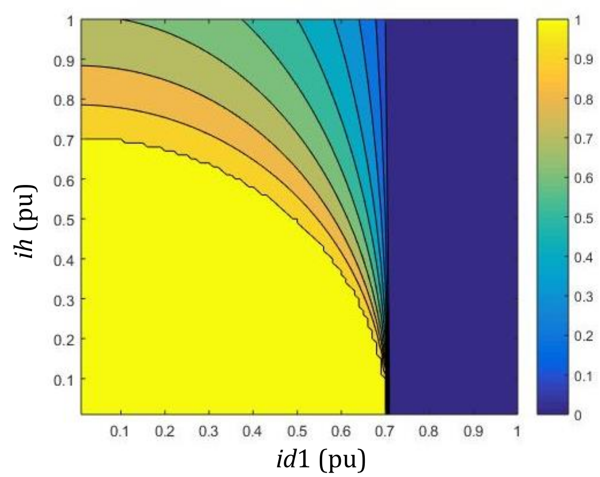

Figure 7: Variation of the coefficient *kr* according to (6)

With the simplifications applied, kr is always smaller than kp. In the practice, the relationship between the two coefficients is more complex, because kr and kp are functions of four variables, and there may be instantaneous current peaks which are not captured by the rms calculation. For this reason, both coefficients kr and kp are calculated and the harmonic currents derating coefficient k is the lowest of the two, as shown in Figure 5:

$$k = \min(kp, kr)$$

III. Numerical Analysis

A. The system under study

Simulations have been carried out on a typical distribution feeder using MATLAB/Simulink. The model is shown in Figure 8 and the component parameters are as follows:

Equivalent system: SCL = 1000 MVA, X/R=10;

PV System: $Pnom$= 500 kW, Vdc = 680, Rs = 5 mΩ, Ls = 2 mH, Vdc = 680 V; PV Transformer: $Vpri$ = 33 kV, $Vsec$ = 354 V, Z=10%; Control: f_{PWM} = 2kHz, kp = 0,5; ki = 700; PF=1

NLL: Rating = 57 kVA rated three-phase diode bridge

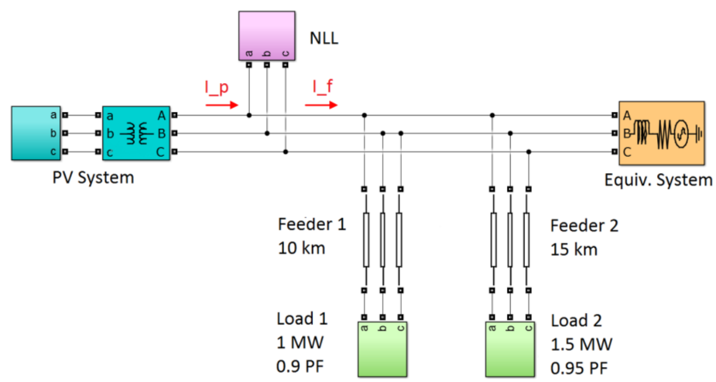

Figure 8: Overview of the simulation model

B. Simulation Results

The simulation cases presented in this section illustrate the use of the proposed control system described to reduce the level of harmonic currents on a feeder.

Figure 9 illustrate results for the case when no harmonic compensation is implemented. The first graph shows Phase A current at the primary side of the transformer (I_p in Figure 8), while the second graph shows Phase A current on the feeder (I_f in Figure 8). For t<0.4 s, the inverter operates close to full power and the harmonic load is not connected. Both primary current I_p and feeder current I_f are sinusoidal. At t=0.4 s, the harmonic load is connected, and this causes distortion in the feeder current, while the primary current remains sinusoidal, since harmonic compensation is not activated. At t=0.5 s, the utility request curtailment of the inverter power output; as a result the transformer current and the feeder current amplitude decrease, with harmonic content unchanged.

Figure 10 shows the same simulation with harmonic compensation implemented. A third graph is added to illustrate the variation of the coefficient k. For t<0.4 s, the inverter operates at full power and the load is not connected. The coefficient k is equal to zero because the inverter operates close to full rating. At t=0.4 s, the harmonic load is connected, and the feeder current is distorted. Since the coefficient k is equal to zero, the inverter does not generate harmonic currents. At t=0.5 s, the utility the utility request curtailment of the inverter power output. Once the power has been sufficiently reduced, at *t*=0.68 s, the coefficient *k* starts increasing to unity. As a result, inverter is allowed to inject harmonic currents, the transformer primary current is distorted and the level of harmonics in the feeder current decreases. The reduction is more evident when the feeder current is compared to the waveform shown in Figure 9.

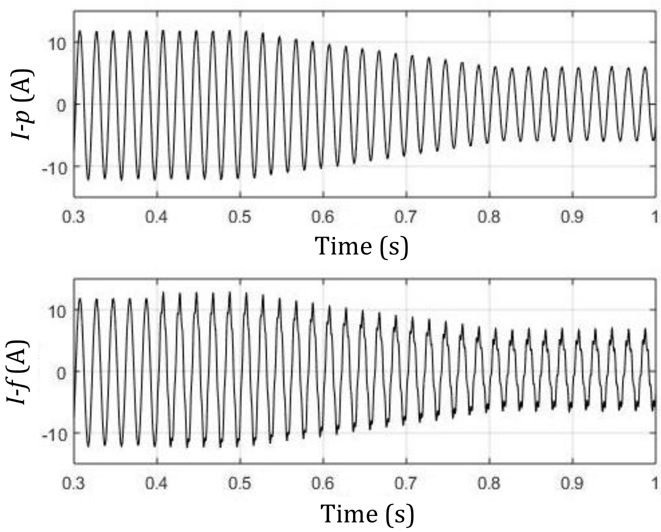

Figure 9: Results with no compensation implemented: primary current I_p and Feeder Current I_f

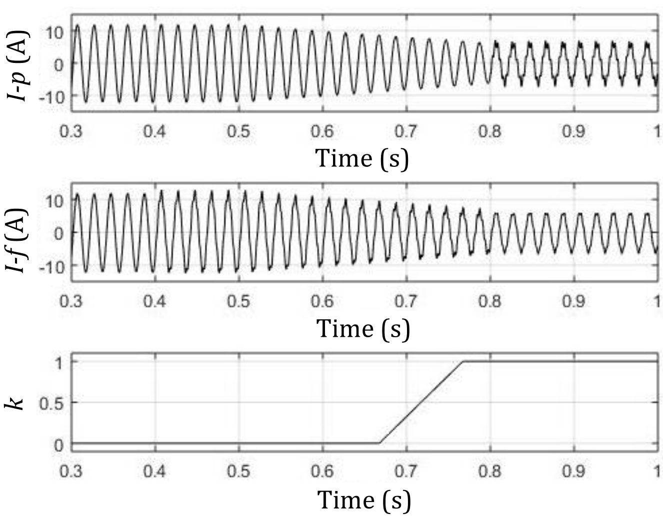

Figure 10: Results with no compensation implemented: primary current I_p, Feeder Current I_f and harmonic current derating coefficient *k*

C. *Applications in practical distribution systems*

The simulation results shown above indicate that the proposed application is advantageous for the utilities, since at peak conditions the feeders may experience high levels of harmonic currents. If a utility is already implementing curtailment to the PV power output, the application proposed in this paper does not require any additional communication port. From the point of view of the PV developer, implementing AF operation requires a modification of the inverter control algorithm, and is justified if a compensation scheme is provided for this ancillary service. This remuneration may compensate, at least in part, for the loss of revenue caused by power curtailment.

IV. Conclusion

This paper presented a control strategy to use a PV inverter as an AF. A harmonic current derating coefficient *k* has been introduced to limit the inverter output current to rated value. The proposed application has practical implementations in smart distribution systems where the utilities curtail power generation from PV inverters when the grid limits are reached. Future work on this topic include: implementation of zero-sequence harmonic currents compensation, the implementation of other ancillary services, and coordination of different DRs to identify the optimal ancillary services to be provided based on system conditions.

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