

Sizing of Step-Up Transformers for PV Plants through a Probabilistic Approach

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Abstract: - Step-up transformers are used to connect large PV plants to the utility network, their sizing being often accomplished only taking into account the PV plant peak power. However, a largely unpredictable power injection on the main grid is obtained if a too large rated power is selected, leading to grid instabilities. This may result in plant shutdowns, while requiring a remarkable reserve power to be provided by conventional generation systems. On the other hand, a too small transformer lead to the creation of a bottleneck, preventing an optimal exploitation of the solar energy. This situation becomes more complex if the introduction of an energy storage system is considered. In the present paper a design technique is proposed to optimally select the step-up transformer, either on conventional PV plants, either on PV plants with energy storage. It is based on the evaluation of initial and operating costs. Moreover, the effects of induced network instabilities are also considered. Taking into account full life costs optimal solutions have been detected according to the network power control capabilities for a 2 MW PV plant.

Key-Words: - Photovoltaic power systems, Power generation, Transformers, Energy storage, Power Plants, Systems Efficiency.

1 Introduction

Photovoltaic power plants (PV) are today rapidly spreading all over the countries, as a result of specific governmental policies, powered by strong climate concerns [1-4]. As shown in Fig. 1, in a traditional PV plant a large number of PV modules are series connected in long strings and a single centralized inverter provides the voltage inversion. Step-up transformers are required to boost the 480÷690 V inverters output voltage to the 13.8÷46 kV of the medium voltage utility network [4]. The string architecture is however burdened by a low efficiency. Therefore, more sophisticated architectures have been developed where PV modules are arranged in strings, or even substrings, each one connected to the step-up transformer through a dedicated inverter, or a dedicated DC/DC converter and a centralized inverter.

Conventional distribution transformers are widely used, either singly or paralleled, to connect the inverter to the main power line. The step-up transformer is a key element of a PV system, as it processes the whole generated energy. Moreover, not only the efficiency and the cost are of primary

concern, but also the influence of the transformer size either on the amount of energy delivered to the main utility, either on the stability of the network. In fact, while selecting a transformer rated power close to the PV plant peak power makes theoretically possible to fully transfer the captured solar energy to the utility network, such a design criterion will in practice lead to oversize both the transformer, the inverter and the power line.

Moreover, a too large transformer would operate for long times at a reduced efficiency, while generating a largely unpredictable power injection on the main grid [6-9]. The last may lead to grid instabilities, causing frequent plant shutdowns, and requiring a remarkable reserve power to be provided by conventional generators. On the other hand, a too small step-up transformer would constitute a bottleneck, preventing an optimal exploitation of the solar energy.

A PV energy plant is quite unreliable, because of the stochastic nature of the solar irradiation [10-14]. To allow such a plant to match the standard requirements for grid stability some forms of energy storage can be introduced. The idea of locally

storing energy to avoid network instabilities and to reduce the size and cost of power lines serving PV plants or wind turbines is not new [15, 16]. Several traditional energy storage technologies have been considered to accomplish this task. Among them: pumped hydroelectric storage, batteries and compressed air energy storage. Moreover, in the last years, some advanced technologies have been also developed including: flywheels, superconducting magnets, fuel cells with electrolyzers and redox flow cells. The last technology, in particular, today appears very promising, requiring inexpensive infrastructures if compared with pumped hydroelectric and compressed air energy storage, while making possible to store energy on longer terms if compared with flywheels and superconducting magnets. Finally, redox flow batteries are less expensive and more reliable than fuel cells and conventional batteries.

The selection of the rated power of the step-up transformer becomes more complex when considering a PV plant with energy storage capabilities, as an optimal solution must be detected taking also into account the features and the cost of the Energy Storage System (ESS) and their effects on the cost and efficiency of the whole system.

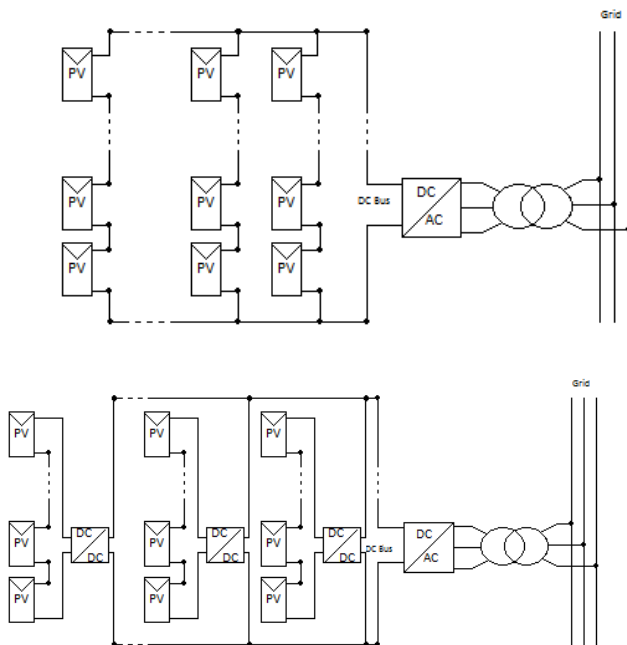


Fig. 1. String arranged (up) and decentralized (down) PV arrays with centralized inverter.

In general, the selection of the step-up transformer in a PV plant is a quite complex task as several variables depending on the transformer rated power must be taken into account as: initial cost of

the system, energy losses due to transformer efficiency, energy storage system efficiency and possible plant disconnections due to grid instability. The aim of this work is to develop a general methodology to accomplish an optimal sizing of step-up transformers for PV plants, either directly delivering power to the utility network, either equipped with energy storage systems [17,18].

2 Step-up transformers for conventional PV plants

The cost of the step-up transformer for a PV plant can be evaluated as a composition of four contributions, namely:

- initial cost
- cost of the energy wasted due to transformer overloads
- cost of energy wasted due to transformer efficiency
- cost of energy wasted due grid instability

2.1 Initial cost

Even conventional distribution transformers are widely used as step-up transformers for PV plants, their customer price can be hardly estimated. In fact, they often are custom built units with unlisted prices. Only considering commercial off the shelf transformers and neglecting taxes and marketing markups, the cost curve of Fig. 2 can be considered, as function of the rated power. Main contributions to the final cost are given from manufacturer selling price, shipping and installation costs. Moreover, as the size and the cost of the inverter serving the plant are also closely related to the transformer rated power, a specific cost function, shown in Fig. 2, is assumed.

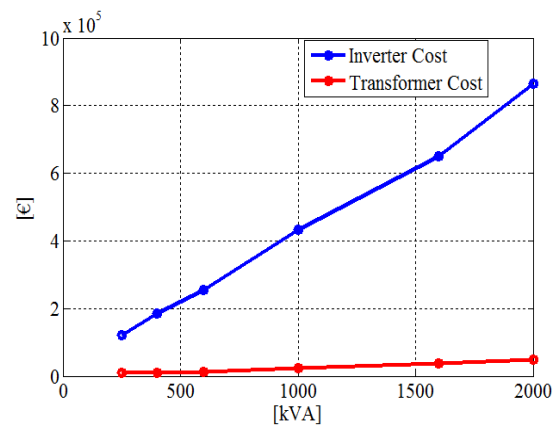


Fig. 2. Step-up transformer and inverter initial costs

2.2 Energy losses due to transformer overloads

Starting from an average daily solar irradiation profile, as that of Fig. 3, the transformer input power P_i can be computed as:

$$P_i(t) = Irr(t) S \eta_{PV} \quad (1)$$

$$E_i = \int_0^T P_i(t) dt \quad (2)$$

where: S is the total net area of PV modules, $Irr(t)$ is the solar irradiation at time t and η_{PV} is the overall efficiency of PV panels and the power converters.

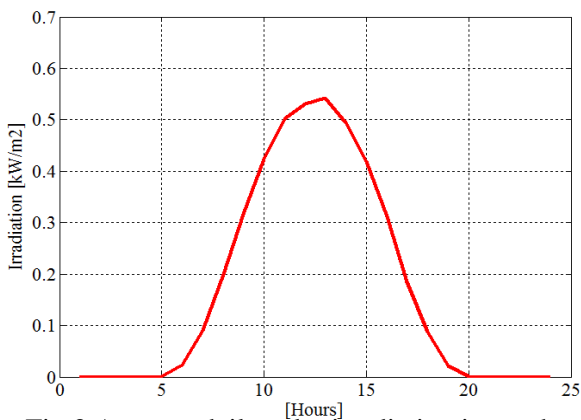


Fig 3. Average daily solar irradiation in southern Europe.

Depending on to the transformer rated power, some of the energy captured by PV modules cannot be delivered to the utility network.

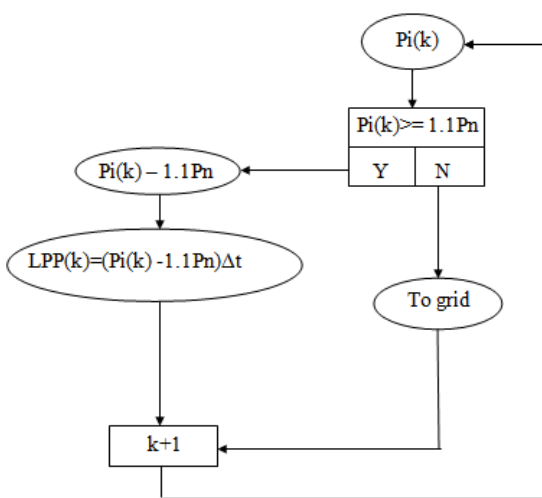


Fig 4. Flowchart of the LPP algorithm

In order to evaluate the energy loss due to transformer overloads a probabilistic approach is

followed based on the LPPP (Loss of Produced Power Probability) index. Such an approach derives from the well-known LPSP (Lost of Power Supply Probability) technique used on PV plants operating in island mode [19-24].

To accomplish the LPPP analysis over a given time window T the last is divided into N intervals, each one $\Delta t = T/N$ long. Typically, these intervals are taken to be of one hour duration. It is assumed that: if $P_i(k)$, the average input power during the k -th interval is greater than 110% the transformer rated power P_n , the excess power is lost, as it cannot be processed. For each k -th time interval, the LPP (Loss of Produced Power) parameter is computed according to Fig. 4.

The value of the LPPP index is then determined as follows:

$$LPPP = \frac{\sum_{k=1}^N LPP(k)}{\sum_{k=1}^N P_i(k) \Delta t} \quad (3)$$

The LPPP index is zero when the maximum amount of the solar energy captured over a day by PV modules is effectively delivered to the utility grid. The lost energy and the associated cost are evaluated as follows:

$$E_W = \sum_{k=1}^N P_i(k) \Delta t LPPP \quad (4)$$

$$C_{EW} = E_W C_e \quad (5)$$

Being C_e the energy selling price per kWh.

2.3 Energy losses due to transformer efficiency

The power wasted due to no load and copper losses during the k -th interval can be computed through the following equation, assuming constant the amplitude of the inverter output voltage:

$$P_d(k) = P_v + \frac{P_c}{P_n^2} P_i^2(k) \quad (6)$$

where: P_v represents the no-load losses and P_c the rated copper losses.

The total energy wasted due to transformer power losses and the associated cost are then obtained as:

$$E_D = \sum_{k=1}^N P_d(k) \Delta t \quad (7)$$

$$C_{ED} = E_D C_e \quad (8)$$

2.4 Energy losses due to grid instability

$$E_{lost} = kP_{pk}N \tag{9}$$

$$C_{E_{lost}} = E_{lost} C_e \tag{10}$$

being P_{pk} the peak output power of the plant and N the total time in hours per year in which the system is disconnected from the utility grid for stability reasons.

2.5 Transformer size selection

Considering a 2MW peak power PV plant, the transformers whose main data are summarized in Table I have been selected for comparison. To simplify the comparison only single units are considered, working at unity power factor [25]. However, the proposed approach can be easily generalized to transformer banks working at an arbitrary power factor. Estimating in 25 years the lifetime of the PV plant, total energy losses have been first computed as shown in Fig. 5.

TABLE I –Step-up Transformers main data

Rated power [kVA]	P_v [kW]	P_c [kW]
250	0.52	2.60
400	0.74	3.62
600	1.04	5.20
1000	1.3	8.97
1600	2	13.00
2000	2.4	16.08

The utility grid is forced to work around the point of balance between the power demand and the generated power. A suitable control system, in fact, manages the reserve conventional generation power to maintain the stability of the entire network. The solar irradiation is intermittent; moreover it often unpredictably varies according to the weather conditions. Therefore, the utility control system sees the power stream generated by a PV plant as a disturbance. The control system is able to compensate such a disturbance only until the delivered intermittent power represents a small share of the total power of conventional generators connected to the grid. Such a share differs from country to country, but it ranges between 5 and 25%. The injections on the grid of different power plants often lead to an huge instability, varying frequency and amplitude of the voltage of the grid. If these variations exceed the standard operative

range defined by the local grid code, the inverter must be disconnected from the grid. Therefore, a large PV plant without energy storage is fairly subjected to frequent shutdowns to maintain the network stability. This causes additional energy losses. Energy losses caused by network instabilities can hardly be predicted in a general way. However, it is plain that they depend from PV plant peak power and the utility network stability margins [26] Assuming that an average shutdown consists of a four hours long full plant disconnection, centered on the peak of the solar irradiation, the energy lost due to grid instabilities and the associated cost can be computed as follows:

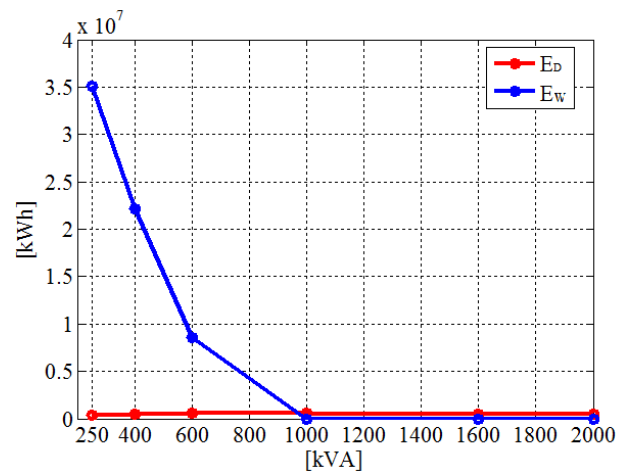


Fig 5. E_D and E_W over 25 years vs. rated power.

Energy losses over 25 years due to grid stability have been also evaluated as shown in Fig. 6 as function of N .

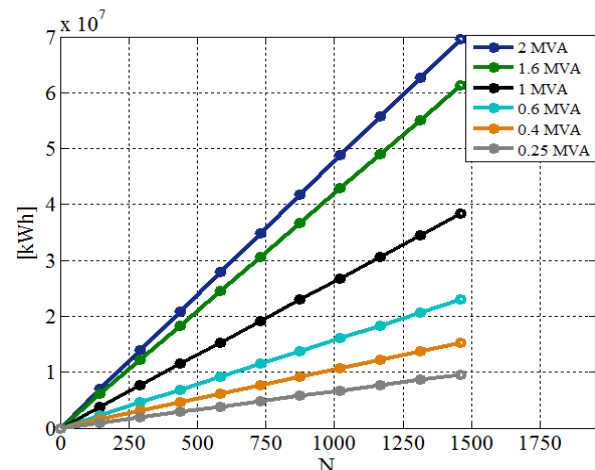


Fig 6. E_{lost} over 25 years vs. expected hours of disconnection per year.

The cost of energy losses over 25 years has been then calculated and added to the initial cost of the transformer and the inverter. Taking also into account

a 3% annual rate of interest, the life costs of the transformer and the inverter have been computed. Estimated life costs are then subtracted to the total price of the energy delivered to the main utility in 25 years. As shown in Fig. 7 the most advantageous transformer is that rated at 1 MVA.

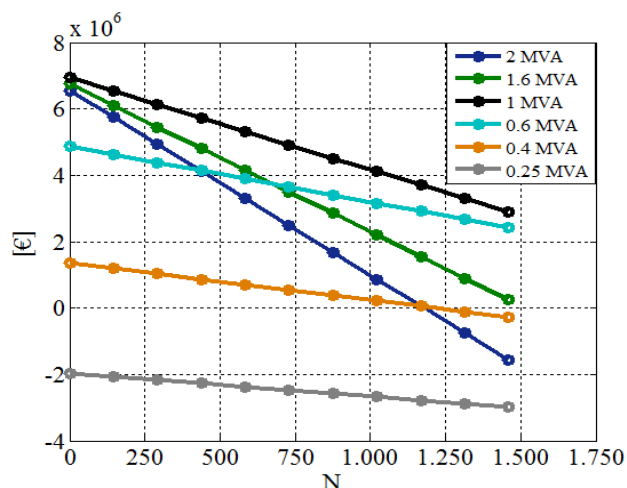


Fig 7. Total life cost vs. expected hours of per year.

3 Transformer for PV plants with energy storage

Vanadium Redox Batteries (VRB) have been selected among available energy storage systems to equip the considered PV plant. In a VRB-ESS the energy is transferred to the electrolyte, rather than being stored into the electrodes as in conventional batteries. As a result, a VRB-ESS can be easily charged, discharged and recharged over 10,000 times (from 20% to 80% of the state of charge) with a high efficiency (65% ÷ 75%), while ensuring a power availability greater than 98%. Moreover, a VRB-ESS is easily scalable either in power, either in storage capability, respectively acting on the number of flow cells and the size of the electrolyte tanks.

If compared with lead-acid batteries, VRB show some advantageous features, such as: compactness, shorter charge times, an increased discharge depth, longer lifetimes and lower maintenance costs.

Moreover, VRB systems are suitable to perform either short time operations, such as compensation of load peaks and voltage drops, either medium or long time operations, as required by energy management strategies.

3.1 Initial cost

In this case the cost of the energy storage system must be added to the cost of the transformer and of the inverter. A cost curve for large VRB ESS is shown in Fig. 8.

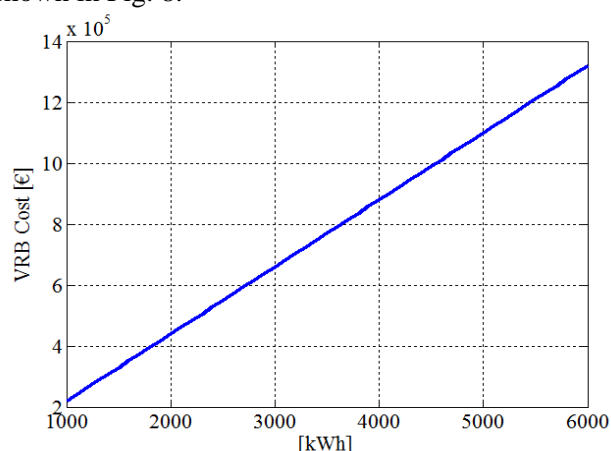


Fig. 8. VRB Energy Storage System initial cost.

3.2 Energy losses due to transformer overloads

The LPP is computed for each k -th interval according to the flow-chart reported in Appendix A. If $P_i(k)$ is larger than 110% the transformer rated power, the excess energy can be stored into the VRB ESS, taking into account conversion and charge efficiencies. However, if the state of charge of the ESS is nearly 100% the excess energy is lost. Moreover, if the excess power outreaches the VRB ESS maximum power P_{ESSMAX} the surplus energy is lost. If $P_i(k)$ is lower than the transformer rated power, some energy is drawn from the VRB ESS to keep the transformer at the maximum efficiency working point. Moreover, if $P_i(k)$ is greater than P_{out} the input power corresponding to the maximum efficiency working point, all the power is delivered to the utility network. If not, some power is provided from the energy storage system.

The LPPP index, the lost energy and the associated cost can be evaluated according respectively to eqs. (3), (4) and (5).

3.3 Energy losses due to transformer efficiency and grid instability

The power wasted due transformer losses during the k -th interval can be computed through eq. (6), while associated lost energy and cost through eqs. (7) and (8) respectively.

A PV plant equipped with an energy storage system is able to modulate the power delivered to the grid, leading to fewer shutdowns if compared

with a PV plant featuring the same peak power but no energy storage. In order to compare PV plants with and without energy storage an equivalent total amount of hours per year in which the system is disconnected from the utility grid is defined as:

$$N^I = \frac{\Delta P}{P_{pk}} N \quad (11)$$

being ΔP the power variability, defined as the difference between P_{pk} and the minimum value of the power delivered to the utility grid over a day (zero if no energy storage is provided). According to eq 11 the total length of grid disconnections is quite conservatively considered proportional to the variability of the power generated by the PV plant. Therefore, without energy storage ΔP is equal to P_{pk} , giving $N^I=N$. At the contrary, if a suitable energy storage system holds constant the power generated over a day, N^I becomes zero. In fact, if the generated power is constant and fully predictable, no interference to the grid stability may occur. Under the above mentioned hypotheses, the energy lost by a PV plant due to system instabilities, can be estimated as:

$$E_{lost} = P_{pk} N^I = \Delta P N \quad (12)$$

Different hypotheses can be easily also considered, as partial disconnections, or average plant disconnections featuring different lengths. Additional costs due to possible system shutdowns can be computed through eq. 10.

3.3 Transformer size selection

The 2 MW PV plant previously described is here considered including a VRB-ESS featuring a 75% round trip efficiency. Three different design approaches have been considered, namely:

1. A VRB ESS featuring the minimum size to ensure $LPPP=0$ (maximum solar energy delivered to the utility grid), while holding the transformer working at the rated power.
2. A VRB ESS able to ensure $LPPP=0$, while holding the transformer working at the maximum efficiency during the discharge of the energy storage system.
3. A VRB ESS able to ensure $LPPP=0$, while holding the transformer working at 99% of the maximum efficiency during the discharge of the energy storage system.

In any case the energy balance over a day must be nearly zero, to ensure that the final state of charge

of the energy storage system is close to the initial value. The first approach lead to the minimization of the transformer rated power.

The second approach lead to the maximization of the average system efficiency.

The third approach has been considered as an attempt to reduce the cost of the VRB ESS, only slightly lowering the average system efficiency.

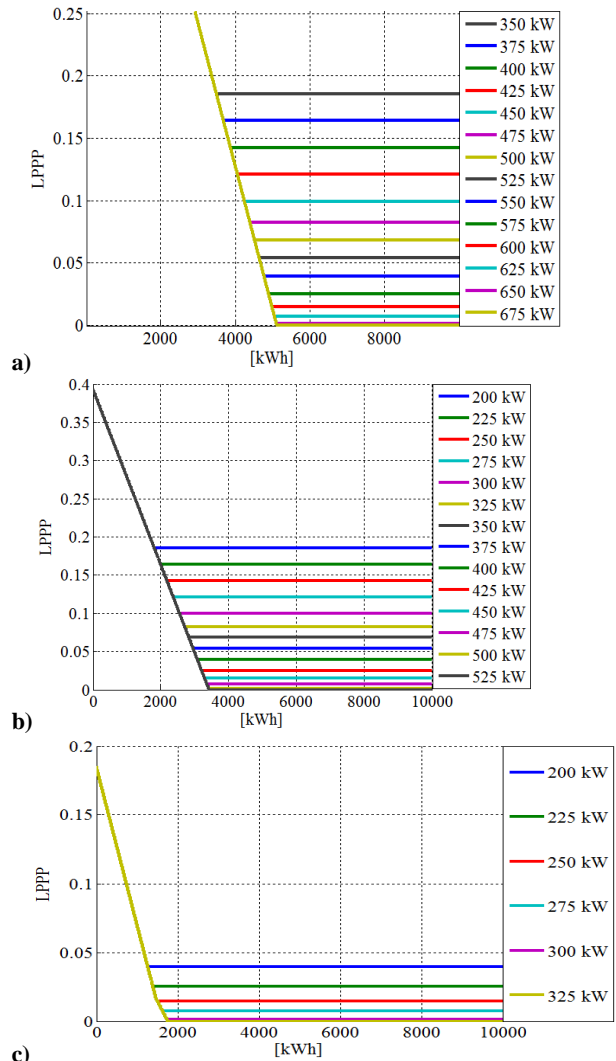


Fig 9. LPPP index for a) 250, b) 400, and c) 600 kVA transformer.

A VRB ESS can be independently sized on storage capacity and power. Therefore the LPPP index analysis has been exploited to find the most advantageous combination among: transformer rated power, VRB ESS energy storage capability and VRB ESS maximum power, for the three approaches.

Considering the transformers whose data are shown in Table I, optimal solutions for the three considered approaches are reported in Table III. In Fig. 9 the LPPP index for different values of

VRB ESS energy storage capability and maximum power is shown for the three selected solutions.

TABLE II – PV plant with energy storage : selected solutions

<i>Design Approach</i>	<i>Transformer [kVA]</i>	<i>VRB ESS [kWh]</i>	<i>VRB ESS [kW]</i>
1	250	5200	675
2	400	3600	525
3	600	1800	325

Results of some simulations dealing with the behaviour of the three selected solution over a day are shown in Figs. 10 and 11. Specifically, the VRB ESS state of charge and the transformer efficiency over an average day, according to the three solutions are shown.

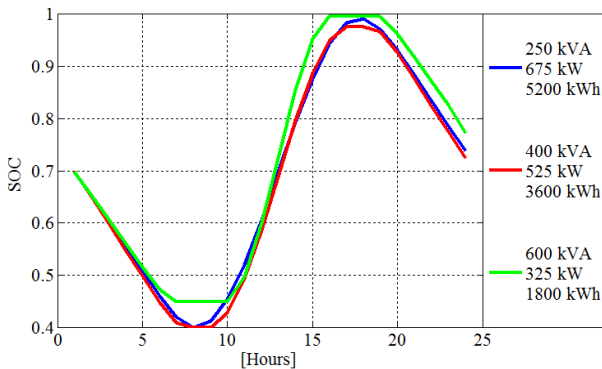


Fig 10.VRB ESS state of charge over a day.

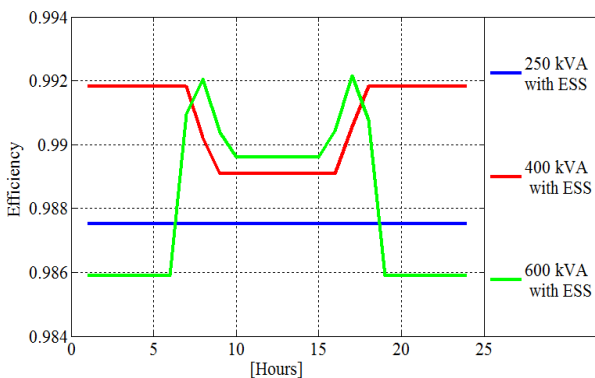


Fig 11.Transformer efficiency over a day.

As in systems without energy storage, energy losses over 25 years due to grid stability have been computed, as shown in Fig. 12 for the three solutions and for different values of N.

The life cost of the three selected solutions has been computed also considering the initial cost of the energy storage system. Life costs have been then subtracted to the proceeds of the sale of energy over 25 years. Obtained results are shown in Fig. 13 and compared with the best solution obtained without energy storage.

As it is possible to observe for very stable utility grids the most advantageous solution is indeed that without energy storage.

However, decreasing the grid stability margins, PV plants with ESS perform better. Specifically, over an expected global duration of shutdowns larger than 140 hours per year, the PV plant with a 600 kVA transformer and a 1800 kWh VRB ESS is progressively more advantageous.

Over 850 hours per year of expected plant shutdown, the most advantageous solution is that with a 400 kVA transformer and a 3600 kWh VRB-ESS.

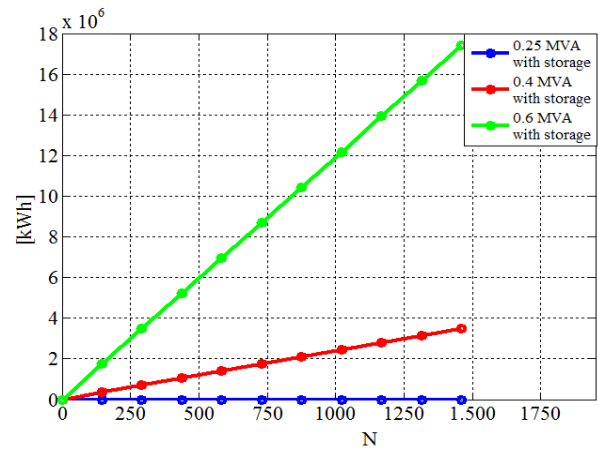


Fig 12. E_{lost} over 25 years vs. expected hours of disconnection per year.

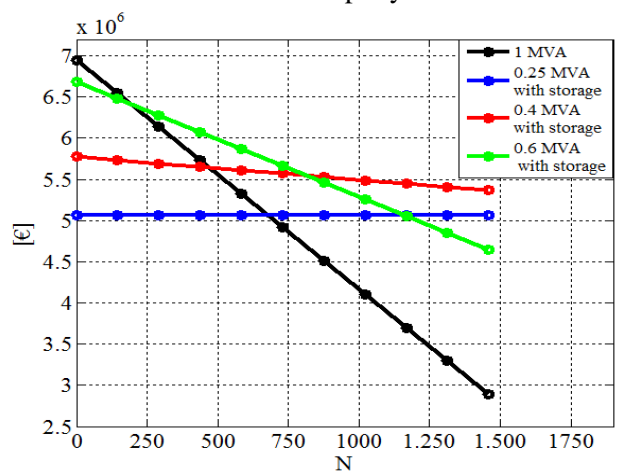


Fig 13. Total life cost vs. expected hours of disconnection per year.

4 Conclusions

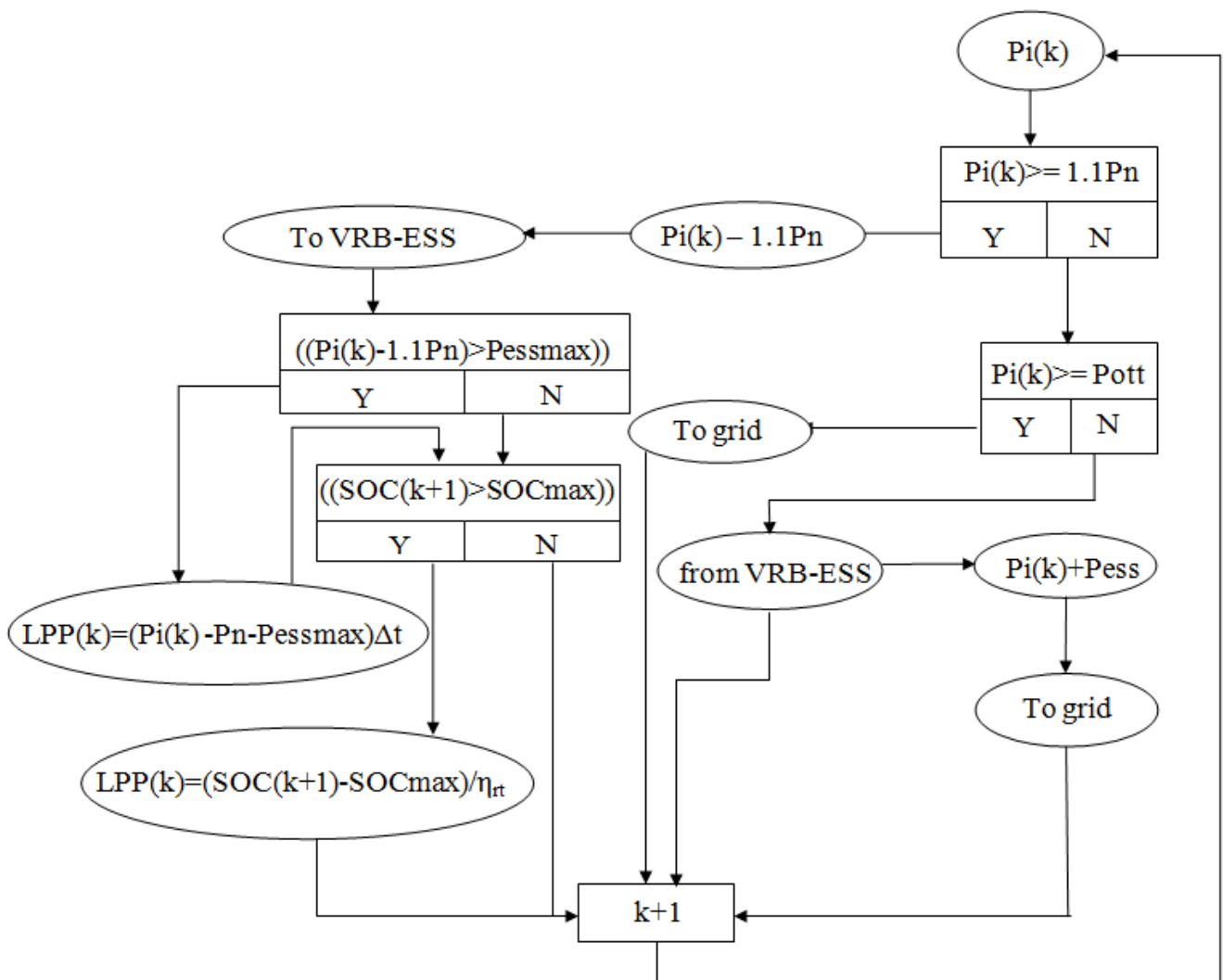
A general methodology to accomplish an optimal selection of the rated power of step-up transformers in PV plants with or without energy storage systems has been presented.

A correct selection of size of the step-up transformer in a PV plant involves a deep analysis of the whole system, as several variables are related to the transformer rated power as: initial cost of the system, energy losses due to transformer efficiency, energy storage system efficiency and the expected

number of plant disconnections due to grid instability.

The proposed approach is based on the evaluation of a probabilistic index the LPPP, to estimate the costs of energy losses related to the size of the transformer and the power and the storage capability of the ESS. Moreover, energy losses related to grid instabilities are also considered. Taking into account full life costs optimal solutions can be detected according to the grid power control capabilities.

APPENDIX A



Flowchart of the LPP algorithm.

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