Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Sizing of Photovoltaic Sources and Storage Devices for Stand-alone Power Plants

R. Rizzo, *Senior Member, IEEE*, L. Piegari, *Member, IEEE,* P. Tricoli, *Member, IEEE,*
C. Munteanu, *Member, IEEE* ,V. Topa

Abstract—**The paper deals with the sizing a PV based source capable of working stand alone. The objective in the design of a PV system is to provide reliable power supply to the load without interruptions and without wasting energy. Several methods for evaluating the achievement of the above objective were found in the literature. In the paper authors proposes a method to size, in one step, the source and the storage systems. In this way it is possible to achieve an optimal sizing with a consequent reduction of plant costs. The resulting system has to be capable of satisfying the load demand in all the weather conditions. Numerical simulations have been effected to show the effectiveness of the proposed method and the capability of the sized system of supplying the load under real working conditions.**

I. Introduction

Photovoltaic and wind energies seem to be the most promising renewable sources for distributed generation.

For remote and rural users, the use of renewable energy sources is particularly convenient, because it is less expensive than the connection to the power grid by means of a dedicated line. Some technical aspects of considerable complexity, concerning mainly sizing and management of the devices of the photovoltaic plants, need to be taken into account such as the stochastic nature and the discontinuity of renewable sources. Both are due to weather factors as solar irradiation. Their evaluation in each selected location can be made by means of forecast mathematical models. These models are complex and the forecast of weather conditions is accurate only for short periods.

The objective in the design of a PV system is to provide reliable power supply to the load without interruptions and without wasting energy. Several methods for evaluating the achievement of the above objective were found in the literature. PV installations have, however, some disadvantages. They tend to have a high initial investment cost which is directly proportional to the size of the system. Storage of the electric energy produced is not 100% efficient, and tends to be quite onerous as well. Therefore and in order to maximize the economic feasibility of PV installations, it is necessary to optimize their size. Such task involves finding the least costly combination of array size and storage capacity that meets the needed load requirements. A preliminary analysis consists in the evaluation of the minimum size of the generation system capable of ensuring the continuity of the supply to the load. This analysis must take into account also the sizing of the storage system and its characteristics: efficiency, charge and discharge time, depth of discharge and so on.

From the analysis of the technical literature it is clear the necessity to define some sizing criteria opportunely tuned on the load specific requirements. Therefore, a theoretical analysis focusing on the sizing problem and the relationships between the different components of the system has been carried out. In the author's opinion, it is always necessary to establish an analytical dimensioning criterion capable of giving a first sizing of the system; from this value, by means of probabilistic methods or numerical simulations, it is then possible to obtain the optimal size of the components of the system. In order to define the first sizing point, it is possible to neglect the randomness of the generated power and of the required load. So, the power generated and the power request will be considered known and periodic [1].

The sizing methods for PV systems are classified into two categories: simulative methods, for example [2], and analytical methods, for example [3,4,5]. The simulation could be applicable when no sizing procedure is established. But it cannot avoid many trials and errors to make the sizing properly. In the preliminary design, it is important to offer easily an appropriate system. Therefore, the analytical methods are chosen in this paper. The analytical sizing methods could be categorized into three types. They are based on as follows:

loads and irradiation [5], available areas [3], LOLP (loss of load probability) [4].

The sizing method based on LOLP is a method that presents combinations of a PV array capacity and a battery capacity which makes LOLP at the desired level analytically. But it is applicable to the PV systems which consist of only PV arrays and batteries and has few sizing examples. On the contrary, the sizing method based on available areas is usually applied to utility-connected systems with bidirectional power flow and it gives a PV array capacity under the available areas, such as roofs. The sizing method based on loads and irradiation is usually used in stand-alone systems including hybrid systems and it can size appropriate PV systems evaluating loads, irradiation and all of the system losses.

R. Rizzo is with Department of Electrical Engineering University of Naples Federico II, ITALY (e-mail: renato.rizzo@unina.it).

L. Piegari is with Department of Electrical Engineering Polytechnic of Milan, ITALY (e-mail: luigi.piegari@polimi.it).

P. Tricoli is with Department of Electrical Engineering University of Naples Federico II, ITALY (e-mail: ptricoli@unina.it).

C. Munteanu is with Department of Electrical Engineering Technical University of Cluj-Napoca, ROMANIA (e-mail: calin.munteanu@utcluj.ro).

V. Topa is with Department of Electrical Engineering Technical University of Cluj-Napoca, ROMANIA (e-mail: vasile.topa@utcluj.ro).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

II. Preliminary Analysis for the Evaluation of the Energy Produced by Photovoltaic Arrays

The sizing procedure of sources and storage systems for stand-alone power plants requires a preliminary analysis of the energy generated by photovoltaic arrays. This is mainly dependent on the orientation and tilt angle of the arrays respect the horizontal plane and the local solar radiation. The orientation and tilt angles of arrays are usually known, whereas the solar radiation incident on a PV module is stochastic, because it is strongly dependent on weather conditions. The problem can be solved starting from the knowledge of the geographic coordinates where the arrays are located and introducing suitable stochastic functions that describe environmental conditions. The solar radiation for sunny days can be evaluated according to the method suggested by the standards UNI 8477 [6] and UNI 10349 [7]. In these standards, the daily average radiation per month, H, can be calculated as follows:

$$H = R\,H_h\,, \tag{1}$$

where H_h is the daily average solar radiation, expressed in W/m^2, and R is a coefficient defined by the following equation:

$$R = \left(1 - \frac{H_d}{H_h}\right) + R_b \frac{H_d}{H_h}\frac{1+\cos\beta}{2} + \rho\frac{1-\cos\beta}{2}\,, \tag{2}$$

where H_d is the diffuse irradiation in kWh/m²; H_h is the global irradiation in kWh/m², whose value is tabulated for several sites; ρ is the reflectivity of the ground and is strongly dependent on the condition of the surface; it ranges from 0.04 to 0.75 and the boundary values refer, respectively, to earth roads and snow cover; R_b is the average monthly value of the ratio between the direct and the horizontal irradiation on the surface. It is calculated from the value of H_b and H_{bh} that are the direct solar irradiation respectively with and without obstructions:

$$R_b = \frac{H_b}{H_{bh}}\,. \tag{3}$$

In (3) the daily irradiation on a horizontal surface in presence of obstructions, H_b, is calculated by:

$$H_b = G_0\left[T\frac{\pi}{180}(\omega'' - \omega') + U\left(sen\omega'' - sen\omega'\right) - V\left(\cos\omega'' - \cos\omega'\right)\right]$$

where G_0 is the solar constant, representing the solar irradiance outside the earth's atmosphere at normal incidence and at the mean sun-earth distance (1353 W/m^2); ω' and ω'' are respectively the solar hour angles of the sun appearing and disappearing (for horizontal surfaces without obstructions they correspond to sunrise and sunset); the parameters T, U e V are defined as follows:

$$\begin{cases} T = \sin\delta\left(\sin\varphi\,\cos\beta - \cos\varphi\,\sin\beta\,\cos\gamma\right); \\ U = \cos\delta\left(\cos\varphi\,\cos\beta - \sin\varphi\,\sin\beta\,\cos\gamma\right); \\ V = \cos\delta\left(\sin\beta\,\sin\gamma\right), \end{cases}$$

where β is the tilt angle, γ is the orientation or azimuth angle (see fig. 1) and δ is the monthly average angle that the line Sun to Earth forms with the equatorial plane; it is called declination and depends on the latitude φ.

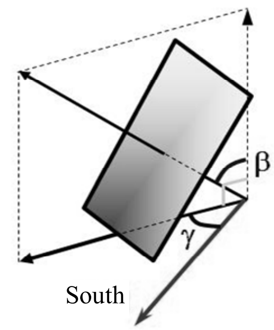


Fig. 1. Surface tilt β and orientation γ angle.

Moreover, the solar irradiance in absence of obstructions, H_{bh}, can be calculated as:

$$H_{bh} = 2G_0\left[T_h\,\frac{\pi}{180}\,\omega_s + U_h\,\sin\omega_s\right], \tag{4}$$

where ω_s is the solar hour angle of astronomic sunrise and the coefficients T_h, U_h and V_h are obtained from T, U e V putting β = 0 (horizontal surface):

$$\begin{cases} T_h = \sin\delta\,\sin\varphi\,; \\ U_h = \cos\delta\,\cos\varphi\,; \\ V_h = 0\,. \end{cases}$$

The evaluation of R requires the knowledge of the ratio H_d / H_h. Unfortunately, data related to the measurements of direct radiation are rare. For this reason, the value of this ratio for the location of interest has to be estimated using a correlation factor. This factor, called clearness index and indicated with the symbol k_T, is evaluated dividing the terrestrial irradiance by the extraterrestrial irradiance:

$$k_T = \frac{H_h}{H_{h0}}\,. \tag{5}$$

Using the clearness index it is possible the evaluation of the ratio H_d / H_h using the table reported in the UNI standards.

The values of H_h are available in the UNI 8477 for different latitudes. The same values are also presented in the UNI 10349 for more sites. In some cases the H_h values of the UNI 10349 substitute the UNI 8477 ones, in other cases they complement each others. The daily data set is obtained from the monthly average values, using a first order autoregressive statistic method [1].

The effect of partly cloudy and overcast days has been taken into account by means of a stochastic procedure. The probabilistic distribution of the number of overcast days in a year is approximately normal, with mean and standard deviation dependent on the site considered [8]. In this paper the rainy days obtained by means of the previous method have been distributed along the year by means of an uniform random variable. The daily clearness index for rainy day ranges between 0.1 and 0.2 for overcast days, and it is equal to about 0.5 for partly cloudy days [9]. Using the daily clearness indexes it is possible to evaluate the incident solar irradiation for the location of interest in different weather conditions; such a value of the irradiance is then used for the estimation of the energy generated by the photovoltaic plant. The production capability makes possible the sizing of photovoltaic arrays and storage devices using the procedure described in the next section.

III. Sizing Procedure of the PV Plant and of the Storage Device

The minimum energy that the PV panels have to supply is equal to the mean value of the power required by the load. This is easily stated taking into account that the storing system cannot contribute to the energy generation. This sizing of the PV plant is the first chosen value used to establish the maximum size of the storing system. Starting from the size calculated in this way, a numerical procedure to find the minimum cost configuration can be used. It has to be taken into account that the increasing of the PV size, starting from the minimum established, implies a decreasing of the storage size. Lead-acid electrochemical batteries are considered as storage device because they are inexpensive and present an energy density greater than that of other devices, like supercapacitors and flywheels.

The knowledge of the time functions $p_G(t)$ and $p_L(t)$, i.e. respectively the power generated and the power demand, makes it possible to select the ratings of the storage device. As in the case considered in [1] the power demand has been considered deterministic; the power generated is instead calculated starting from the stochastic considerations of the distribution along the year of the overcast and partly cloudy days. For each distribution of these days there results a different number of photovoltaic panels and a different capacity of the battery. For stand-alone systems, the difference between the electric power generated by photovoltaic arrays and that drawn by the load is equal to the power of the storage device, $p_S(t)$, if the charge and discharge efficiency of the storage device, η, can be considered equal to 1:

$$p_S(t) = p_G(t) - p_L(t). \tag{6}$$

The power of the storage device for discharge operations has to be at least equal to the absolute maximum of $p_S(t)$; dually, the recharge power has to be at least equal to the absolute minimum $p_S(t)$, changed in sign.

In case the efficiency of the storage device can't be neglected, the size of the photovoltaic arrays has to be increased in order to supply also the losses of the storing device itself. The coefficient of over sizing can be evaluated solving numerically the following equation:

$$A = 1 + \frac{1}{T}\frac{1-\eta}{1+\eta}\int_T \left|\lambda - A\gamma\right| dt. \tag{7}$$

where λ and γ are respectively the powers of the load and of the photovoltaic source referred to their mean values, i.e.:

$$\lambda(t) = \frac{p_L(t)}{\frac{1}{T}\int_T p_L(t)dt}; \qquad \gamma(t) = \frac{p_G(t)}{\frac{1}{T}\int_T p_G(t)dt}. \tag{8}$$

Using (7), the power of the storage system is modified in the following way:

$$p_S(t) = \frac{\left[p_G(t) - A\,p_L(t)\right](1+\eta) + \left|p_G(t) - A\,p_L(t)\right|(1-\eta)}{2\eta_D}, \tag{9}$$

where η_D is the discharge efficiency of the storage system.

The capacity Q_S of the storage device, expressed in J, can be evaluated starting from the integral function:

$$e_S(t) = \int_0^t p_S(x)dx. \tag{10}$$

This function is related to the energy supplied by the storage device from the beginning of the cycle. If the mean values of $p_G(t)$ and $p_L(t)$ are the same, the mean value of the function $p_S(t)$ is zero and therefore $e_S(0) = e_S(T)$, where T is the period of cycle. In order to avoid that the state of charge of the storage device is less than zero, the capacity Q_S has to be at least equal to the maximum variation of the energy supplied during the cycle period. If:

$$E_{S,\max} = \max\left[e_S(t)\right]; \qquad E_{S,\min} = \min\left[e_S(t)\right], \tag{11}$$

are respectively the maximum and the minimum of the integral function $e_S(t)$, the capacity of the storage device has to satisfy the following condition:

$$Q_s \geq E_{S,\max} - E_{S,\min}. \tag{12}$$

Moreover, it is possible to state a minimum state of charge the batteries should reach during the system working. In this way the batteries health is saved and a minimum safety energy is always stored. In order to achieve the minimum state of charge, batteries have to be oversized.

The sizing procedure described strongly depends on the diagrams of the generation and load powers. Moreover, the energy storage is seasonal, i.e. the evaluation of the storage capacity is made on a base of one year. This leads to storage devices very large and, consequently, high costly. Although it is necessary to generate at least the energy required by the load in one year, the photovoltaic arrays can be oversized in order to reduce the capacity of electrochemical batteries. The larger area of arrays allows a lower discharge of the battery during the days of bad weather and therefore a lower battery capacity. Among all possible configurations of photovoltaic arrays and electrochemical batteries, it is possible to find the sizing corresponding to the minimum cost for the system. As stated before, the randomness of the generation power implies generally different sizes of panels and batteries. The problem of the definition of the correct sizing can be done making reference to confidence intervals. In fact for each number of overcast days, a power source and storage device larger than those evaluated by the proposed sizing procedure is surely capable of supplying the load. Performing a representative number of simulations of weather conditions using Monte Carlo methods, there are available a correspondent number of possible sizes of photovoltaic panels and batteries. The final sizes selected are, hence, those satisfying at least 95% of the simulations considered.

IV. Validation of the sizing Method

In order to test the capability of the proposed algorithm of correctly sizing the PV array and the storage system, some numerical simulations have been carried out. In particular, a load has been considered and the proposed criterion has been used to determine the best size of the components of the system. Moreover, the resulting system has been compared with that obtained applying the sizing criteria give by the IEEE Standard 1562-2007 [10] that is a Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems. To carry out the comparison, preliminarily, the capability of supplying the load under real working conditions has been tested for both the systems. Then, the costs of the two systems can be used to verify the possibility to save money using the proposed method instead of the IEEE standard.

The real test conditions have been obtained considering a PV plant to be installed in Rome (latitude 41.29°) for a load whose power peak is 200 W and whose daily hour diagram is reported in fig. 2.

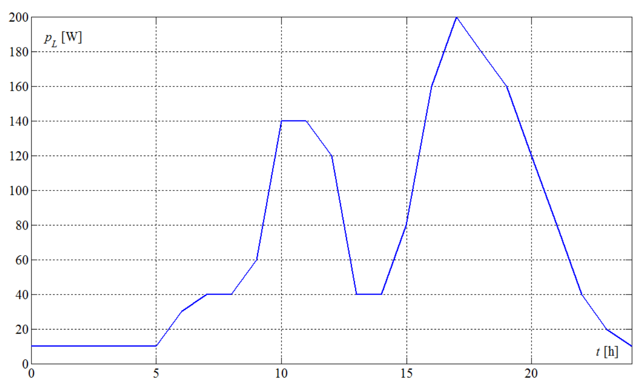


Fig. 2. Simulated hourly load diagram.

The main data of the panel unit to be used to realize the array are reported in tab. I.

Tab. I. Main data of the PV panel unit

P_n [W]	V_{MP} [V]	I_{MP} [A]	$Area$ [m^2]	η [%]
150	12	12.5	1.67	9

It is worth to note that the efficiency has been chosen equal to 9% because, during the years, the actual efficiency of the panels decreases.

In order to test the two systems under actual working conditions the TRY (Test Reference Year) data have been used. The TRY data are mean values of real hourly measured weather data under a period of 20 years. In fig. 3 the radiation incident on the panels of the system, calculated by means of UNI 8477 and UNI 10349, are compared with the total incident radiation given by TRY for the latitude of Rome.

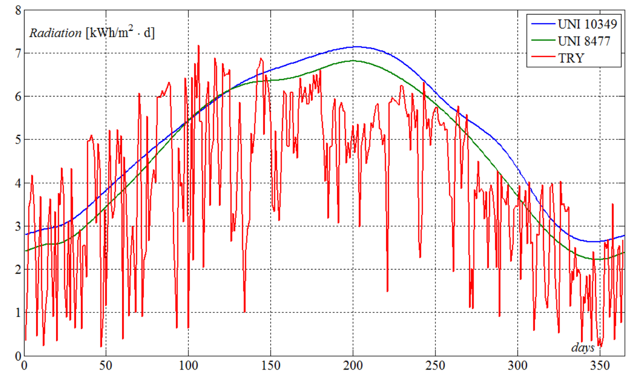


Fig. 3. Solar radiation given by UNI 10349, UNI 8477 and TRY data for Rome latitude.

In order to apply the proposed criterion a generation diagram has to be chosen. First of all, the UNI 8477 standard is used because it estimates a lower radiation in comparison with UNI 10349. Then, it has to be taken into account that the UNI standard gives the radiating energy during clear days. But, some cloudy days are, always, present. As reported in [8] for south Italy the number of cloudy days per year can be represented with a normal distribution whose mean value is 93.5 and standard deviation is 20.4. They are considered uniformly distributed during the year. So, Monte Carlo method has been used to generate 10 thousands possible years.

The application of the proposed algorithm leads to the following size of the system: 8 panels and batteries for 21.2 kWh. Taking into account the cost of 4 €/W for the photovoltaic source and of 13 €cent/Wh for the batteries the total cost of the system is about 7560 €.

The application of the IEEE Std. 1562-2007 leads to a photovoltaic source realized using 11 panels of the kind reported in Tab I. The energy of the storage system to ensure 10 days of autonomy is 17.5 kWh. So, the total cost of the system, sized following the IEEE standard is about 8870 €.

Applying the IEEE standard the maximum installed power results equal to 1650 W, more than 8 times the load power. This is due to the fact that the IEEE standard makes the sizing during the month with the lowest irradiation in order to ensure the energy production in the worst case. This is a consequence of the separate sizing of photovoltaic source and storage batteries. Indeed, the choice of the battery size is totally independent on the PV size and depends only on a number of autonomous days. On the contrary, the proposed method makes in one step the sizing of both the source and the storage system. Harmonizing the two sizes it is possible to achieve an effective money saving of 13.5%.

In order to check the capability of the two system to work in real cases, a simulation of one operating year has been effected using TRY data. In fig. 4 and 5 the state of charge of the batteries of the system sized with IEEE standard and proposed method are respectively reported. From the analysis of the two figures it is clear that both the systems are capable of accomplishing the mission. It is also clear that the sizing of the system obtained with the proposed method implies a seasonal use of the storage system that is much more exploited than in the other case.

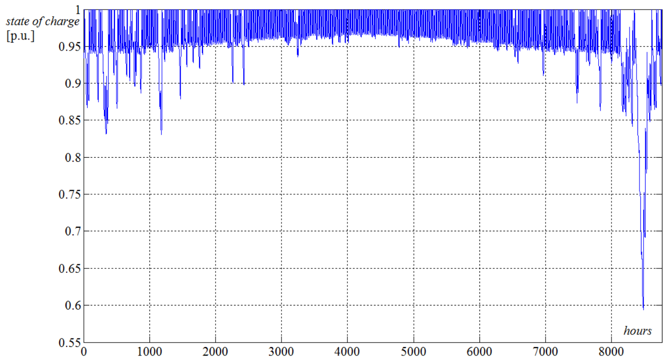


Fig. 4. Battery state of charge for the system sized with the IEEE Std. 1562-2007.

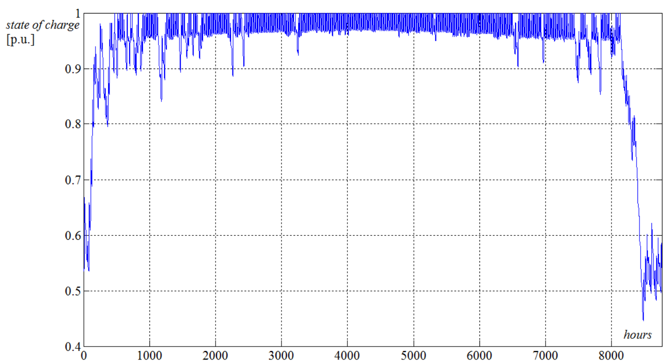


Fig. 5. Battery state of charge for the system sized with the proposed criterion.

It is worth to note that the proposed method is not a traditional LOLP method. Indeed, for each case the choice of the size of the source and of the storage system is obtained by means of an analytical procedure. The Monte Carlo method is used only to take into account the variability of the input energy due to the natural variability of the weather conditions. It is also possible to underline that the hourly load diagram does not affect, in fact, the results. Indeed, the storage system is capable of supplying the load also during some cloudy days. So, only the medium power requested by the load influences significantly the size of the system. The variability of the load during the hours can be, therefore, neglected.

V. Conclusions

The problem of sizing the source and the storage systems for photovoltaic based autonomous energy plant has been analyzed in the paper. The sizing problem is, generally, a very complex problem because of the variability of the load demand and of the source. At present, the sizing energy systems using photovoltaic panels and electrochemical batteries is solved by means of the application of the IEEE Standard 1562 of the 2007. However, this standard solves the sizing problem separately for the source and the storage system obtaining, usually, an oversized system. In the paper, authors have proposed an innovative sizing procedure that allows to obtain a reduced size energy system capable of satisfying the load demand all over the year. The reduced size implies, of course, a money saving.

The proposed procedure has been applied to a real case and has been obtained a system 13.5% cheaper than that suggested by the IEEE standard. The capability of the proposed system of supplying the load has been tested using the TRY data that give measured weather conditions over a period of 20 years. From the results reported it is clear that a sizing of the system that takes into account the seasonal variability of the source is optimal because allows a reduction of the size and then of the cost of the system itself.

VI. References

[1] L. Piegari, R. Rizzo, and P. Tricoli, "Sizing criteria for stand-alone power plants supplied by photovoltaic arrays", *Proc. 2nd International Conference on Modern Power Systems - MPS 2008*, Cluj-Napoca (Romania), 12-14 November 2008.

[2] R. Chapman and J. Fernandez, "SIZEPV: A Simulation Program for Stand-alone Photovoltaic Systems", *User's Manual, Sandia Laboratories*, 1989.

[3] S. J. Strong, "The Solar Electric House: A Design Manual for Home-Scale Photovoltaic Power System", *Rodale Press*, 1987.

[4] J. J. Duffy and S. L. Frye, "An Expert-System-Based PV Sizing Method for Minimum Cost", in *Proc. ASES Annual Meeting*, 1989.

[5] Canada Centre for Mineral and Energy Technology, Energy Mines and Resources Canada, "Photovoltaic Systems Design Manual", 1991.

[6] *Solar energy. Calculation of energy gains for building applications. Evaluation of energy gains coming from active or passive systems*, UNI Std. 8477, 1985.

[7] *Heating and cooling of buildings. Climatic data*, UNI Std. 10349, 1994.

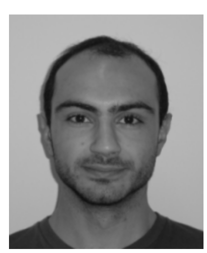
[8] G. Micela, L. Granata, and V. Iuliano, "Due secoli di pioggia a Palermo", *Osservatorio Astronomico di Palermo G.S. Vaiana Università di Palermo*, 2001.

[9] J. L. De Souzaa, R. Mendonça Nicácio, and M. A. Lima Mouraa, "Global solar radiation measurements in Maceió, Brazil", *Renewable Energy*, vol. 30, pp. 1203-1220, 2005.

[10] *IEEE Guide for Array and Battery Sizing in Stand-Alone Photovoltaic (PV) Systems*, IEEE Std 1562, 2007.

VII. Biographies

Renato Rizzo (M'00, SM'06) was born in Naples, Italy. He studied at the University of Naples Federico II and received the Degree in Electrical Engineering. He is professor of Electromechanical Design, Basics of Electrical Drives, Electric Propulsion, Electric Machines Laboratory, at the Faculty of Engineering of University of Naples Federico II. Prof. Rizzo is professor honoris causa of the Technical University of Cluj-Napoca, Romania. He is an IEEE Senior Member, EAEEIE Member, treasurer of ANAE (the National Association of Electrical Drives in Italy). His researches are devoted to electrical machine and drives, and to their applications in transport systems, renewable energy sources . He published more than 100 scientific papers and 2 books and he participated to different research programs. Prof. Rizzo is a Registered Professional Engineer in Italy.



Luigi Piegari (M'04) was born in 1975. He received Master's degree and the Ph.D. degree in electrical engineering from the University of Naples "Federico II," Naples, Italy, in 1999 and 2003, respectively.
Currently, he is assistant professor at the Department of Electrical Engineering Polytechnic of Milan. His current research interests include electrical machines, high efficiency power electronic converters, renewable energy sources, and electrical supplies and cableway plant.

Pietro Tricoli (M'06) was born in Naples, Italy, on September 8, 1978. He received the M.S.E.E. and the Ph.D. degrees in electrical engineering from the University of Naples Federico II, in 2002 and 2005, respectively.

He was a Visiting Scholar in the Department of Electrical and Computer Engineering, University of Wisconsin-Madison. In 2006, he was also a Visiting Scholar in the Department of Electrical and Electronic Engineering, Nagasaki University, Nagasaki, Japan. He is currently a Post-Doc Research Fellow with the Department of Electrical Engineering, University of Naples Federico II. He is the author of more than 30 scientific papers published in international journals and conference proceedings. His main fields of interest are the use of renewable energy sources for road electric vehicles and rovers, the control techniques of asynchronous machines both as motors and generators, and the modeling of active filters. Dr. Tricoli is a Registered Professional Engineer in Italy.

Calin Munteanu (M' 2004) was born in Baia-Mare, Romania, on August 30, 1965. He received the M.Sc. degree in electrical engineering from Technical University of Cluj-Napoca, Romania, in 1989, and the Ph.D. degree in electrical engineering from Technical University of Cluj-Napoca in 1999. He joined the Electrotechnics Department from Technical University of Cluj-Napoca in 1991. Since 2003 he is Professor of Electromagnetic Theory and the Head of the EMC Laboratory. His scientific work is related to electromagnetic fields, numerical computation and measurements, optimal design techniques and EMC in power devices.

Vasile Topa was born in Cluj-Napoca, Romania, on July 29, 1957. He received the M.Sc. degree in electrical engineering from the Technical University of Cluj-Napoca (Romania) in 1982, and the Ph.D. degree in electrical engineering from the Technical University of Cluj-Napoca in 1998. He joined the Electrotechnics Department from the Technical University of Cluj-Napoca in 1985. Since 2001 he is Professor of Bases of Electrotechnics and since 2008, the Head of the Electrical Engineering Department. His scientific work is related to electromagnetic field computation, optimal design of electromagnetic devices and electric circuit analysis and design.