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Participation in Reactive Power Market Considering Generator Aging

Ismail Niazy[1], Hashem Mortazavi[2], Jaafar Ebadi[1], Soheil Sabzevari[1], Abraham Niazy[1]

Abstract – *As one of the most important ancillary services, reactive power production plays a crucial rule in power system operation, reliability and security. Because of the opportunity costs in providing reactive power, producers are under great pressure to provide VAr support. This paper presents a new challenge on the reactive capability curves (RCC) of the synchronous generator taking in account the normal limits of operation without exceeding thermal limitations. The importance of re-evaluation of RCC in the real world is because of the RCC is changed over time and aging of the generators. In this paper it is discusses about some reasons, which lead to the variations, and the importance of re-evaluation of RCC.* ***Copyright © 2010 Praise Worthy Prize S.r.l. - All rights reserved.***

Keywords*: Ancillary Services, Generator Capability Curve, Generator Aging, Reactive Power Market*

I. Introduction

Reactive power is an important system support service in the current power market. Power producers have the opportunity to offer this service to make a profit. Given the fact that a generator needs reactive power to transmit its own active power, however, it is possible that certain generators cannot support a system even if they are generating reactive power [1]. In an open accessed transmission system, the costs of each ancillary service will be unbundled [2].

Synchronous generators are a primary source of reactive power in electric power systems. Although there are other important reactive power sources such as shunt capacitors and flexible ac transmission system (FACTS) controllers, to a great extent, generators are responsible for maintaining adequate voltage profiles across the systems [3]. Consequently, their characteristics and their limitations are of major importance for the analysis of power grids, particularly when the system is operated near its limits.

This is even more relevant under the current competitive market environment, as economic pressures from market participants force the grid to supply the required demand with widely varying suppliers while still guaranteeing the operational and security limits of the system [4]. Therefore, the economic performance of electricity markets is directly related to the level which the systems and especially generators capabilities are fully recognized and deployed.

The stability and security limits of power systems can be closely approximated by voltage stability criteria [5].

In almost all voltage instability incidents, one or more synchronous generators reached its reactive power limits (Q-limits) [6].

Thus, the proper modeling of the reactive power capabilities of generators is of crucial importance for voltage stability studies.

In the majority of the applications, regardless to generator age, it is assumed that the RCC of the generators is fixed and is as the first one provided by the manufactures. So, in the active and reactive power dispatch programs, these provided capability curves are used [7]-[9]. However, in the real world, RCC of the generator are changed over time and aging of the generators. The mentioned changes are caused due to several reasons such as mechanical restrictions in the turbine-generator system and fouling problem in the cooling systems of the generators [10], [11]. In addition, it can be caused by restrictions of the cooling water circulation [12]. Also, limits of the capability curve of the generator, including the overexcited region, underexcited region and region limited by stator current heating, are modified in response to changes in coolant pressure or temperature [13]. These temperature and pressure ratings are designed to maintain the synchronous generator temperature at or below the electrical insulation temperature class limit [14].

Considering this problem, some papers proposed re-evaluation of RCC. for example, in order to improve voltage coordination in [15] it is suggested to re-evaluate RCC; in [16], [17] for an optimal power flow, in [18] to improve transmission system reliability, in [19] to ensure proper operation of exciter controller and protection setting and in [20] in order to run more effective economic dispatch it is suggested to re-evaluate RCC of the generators.

In competitive electricity market, reactive power ancillary service management is a critical task for power system operator. Therefore, the generator owners are

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under great pressure to produce VAr -from both technical and economical perspective- as much as possible.

This paper challenges on the assumption that RCC is constant over time regard to reactive power market. After discussion about the sakes of variation in the generator RCC, this paper presents some ways to test and extract the new and real-time RCC instead of the one provided by the manufacture. Using new extracted capability curves, it is possible for generation companies and power plants to participate in the reactive power market and economic dispatch programs with more confidence, security and reliability [13].

II. Generator Reactive Capability Curve

Generator capability curves or RCC provide a useful tool in the loading of electrical generators. These curves define the normal limits of operation without exceeding thermal and stability limitations. The capability curve or family of capability curves, show the MVAR loading vs. the MW loading over the full range of operation, overexcited and underexcited, at varying coolant pressures. Lines of constant power factor may be indicated to the capability curve by straight lines as shown in Fig. 1. Operation at any load outside of curves limitations will result in overheating.

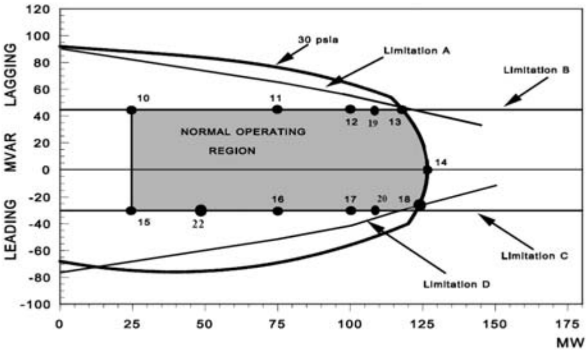


Fig. 1. Reactive capability curve [21]

III. Capability Curves Variations

The limiting factor in each rejoin of the capability curve at the upper boundary at any coolant pressure level is the rotor field thermal limit specified at DC current rating. The right boundary is the synchronous generator stator limit. The lower boundary is the end iron heating limit which occurs during leading power factor, underexcited operating condition. In addition, some limitations are applied by system and protection considerations. For example every machine have a steady–state stability limit that is determined by generator characteristic and the stiffness of the electrical system to which the machine is paralleled. A loss-of-load relay can be set to trip the machine auxiliary relay before this limit is exceeded. Other limitations are minimum excitation limiter (MEL) and underexcitation reactive ampere limiter (URAL) in the automatic voltage regulator. So, the resultant curve is more limited as shown in Fig. 2.

In the majority of the applications such as ancillary services and reactive power markets, it is assumed that the capability curves of the generators do not change over time and are as provided by the generator manufacture. In this paper, this assumption is challenged and it is discussed that with the generator aging, distinctive changes are appeared in RCC due to different causes. In this paper, the RCC variations are categorized into three main parts based on the cause of the variations: the mechanical causes, the electrical causes and power system limitations.

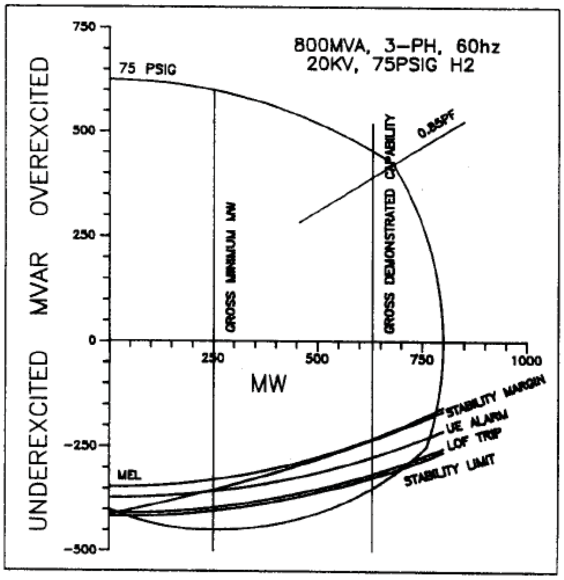


Fig. 2. Capability curve with system protection limits [14]

III.1. Mechanical Causes

Turbine-generator combination has various mechanical and electrical parts. In many reports, the effect of aging on different mechanical parts of the turbo-generators is reported [10]-[12]. The most important limitation factor in the capability curves is the heating problem of the armature and excitation currents [13]. As mentioned in several reports, it is clear that the fouling in the cooling system of the water-cooled generators, limits the flow of the electric current in the windings due to exceeding thermal limits. Fouling has two important effects on the cooling process: first effect is due to flow restriction caused by fouling and second is due to heat transfer defects caused by fouling layer in the skin of the tubes.

Water-cooled generators with hollow copper strands frequently suffer from deposition of copper oxides that clog them and impair cooling water flow. Solubility is one factor governing the release and the re-deposition of copper oxides. Fig. 3 shows copper oxide deposit in the hollow conductor, which restricts follow of cooling water in the hollows.

Another problem caused by fouling is defect heat transfer from skins of the water tubes. The fouling in the internal skin of the water tubes produces deposition and the skin thickness increases and heat transfer decreases subsequently. This is discussed in [11], increment of heat transfer resistance in the skins is shown in Fig .4 as a function of time.

Fig. 3. Copper oxide deposits at the hollow conductor inlet [10]

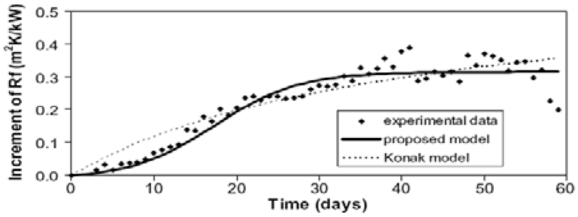


Fig. 4. Increment of the heat transfer resistance in the skin [11]

III.2. Electrical Causes

The electrical materials used in stator and rotor windings have a major impact on the operation of large motors and generators [22]. The main effect of aging on generator as discussed in many reports [22], [23] appears on the insulation of windings and conductors of the windings. These problem results to several kind of phenomenon that are pointed in reports such as [22], [23]:

- Change in insulation resistance
- Increment in DC and AC leakage currents
- Change in polarization index
- Increase in dissipation factor
- Decrement of discharge excitation voltage
- Dielectric absorption variation
- Winding resistance variation
- Winding impedance and pole balance variation

As discussed, several kinds of variations arise in the turbine-generator system, which results in varying the turbine-generator characteristics. Therefore, the capability of the generator on delivery of real and reactive power will change which change the capability curve of the generator. So RCC of the synchronous generators can modify with aging, in other words the assumption of having fixed RCC in the lifetime of generator is not a valid assumption.

Because of mentioned challenges and discussed problems, in some operational utilization it is suggested to re-check the generators RCC in order to extract the new curve for synchronous generators. For example, in some applications it is suggested that, units with a nominal capacity greater than 70 MW should be tested for reactive capability [18]. In [19] it is suggested that the test should be performed for units with more than 10-MW capacity. Therefore, units, which have worked more than 5 years, should be tested and it is suggested that the mentioned test to be repeated every 5-years [18]. In the following section, several methods are suggested for extracting new reactive capability curve of the synchronous generators.

III.3. Power System Limitations

Achievable generator reactive capability is generally much less than indicated by manufacturers' reactive capability curves, due to constraints imposed by plant auxiliaries and the power system itself. The generator reactive capability curves furnished by manufacturers and used in operation planning typically have a greater range than can be realized during actual operation. Generally, these curves are strictly a function of the synchronous machine design parameters and do not consider plant and system operating conditions as limiting factors [15].

Every machine will have a steady-state stability limit, which is a function of both the synchronous generator characteristics and the stiffness of the electrical system to which the machine is paralleled. Many of synchronous generators have additional underexcited capability available because of the electrical transmission system has become stiffer since the issuance of the machine capability curves [14].

IV. Extracting New Capability Curve

As mentioned previously in the past sections, the reactive capability curve of the synchronous generators vary over time, therefore the assumption of that the capability curve to be considered unchanged is not valid. For this reason, in this section some methods, which are used to extract the new reactive capability curve of the synchronous generators, are presented. The methods, which are used to extract new capability curve of the generators, can be categorized in two main methods: First method is direct method, which use direct tests on the synchronous generators to acquire new RCC of the generators. The second method is related to methods, which use indirect approach to acquire new RCC.

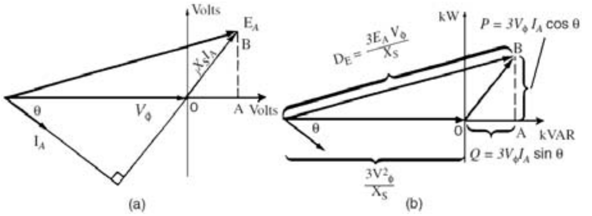
IV.1. Direct Method

In some applications it is suggested that generators should be tested directly to be evaluated in order to new reactive capability curve of the generators be acquired. The direct method is categorized to two subsections itself: approximate method and precise method, which will be discussed in following.

1. Approximate direct method

In some applications, the reactive capability curve of the generators is not accessible and so it is essential that the mentioned curve be acquired. In such cases if the exact curves are not needed, the approximate curves can be extracted using standard methods provided in many documents [24]-[28].

The capability curve diagram illustrates the complex power $S = P + jQ$. It is derived from the generator's phasor diagram, assuming that voltage of the terminals of the generator V_φ is constant at the generator's rated voltage. Fig. 5(a) illustrates the phasor diagram of a synchronous generator operating at its rated-voltage and lagging-power factor. Fig. 5(b) illustrates how the axes can be recalibrated in terms of real and reactive power. This method can be found in [24].



Figs. 5. Derivation of a synchronous generator capability curve. (a) The generator phasor diagram; (*b*) the corresponding power units [24]

Fig. 6 illustrates the final capability curve of a synchronous generator. It illustrates a plot of real power P versus reactive power Q. Additional constraints, such as the maximum prime-mover power, can also be shown on the diagram to accomplish the RCC therefore the resultant capability curve can be extracted such as one shown in Fig. 7.

2. Exact direct method [18]

In some cases, for example in units with high capacity, it is important to have exact reactive capability curve and the approximate curves which acquired by approximate method are not satisfactory. Therefore, it is essential that mentioned curves to be obtained using precise approach. The precise approach is very exact but expensive and time-consuming [18].

Detailed method can be found in documents as [18], and in this paper just a glance to the method is presented.

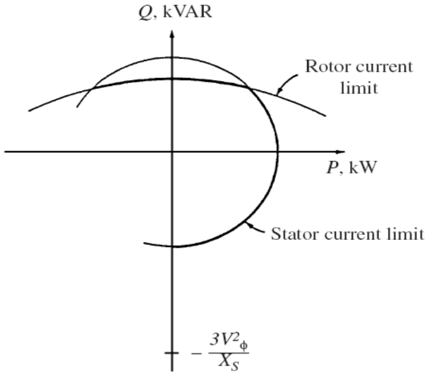


Fig. 6. The resulting generator capability curve [24]

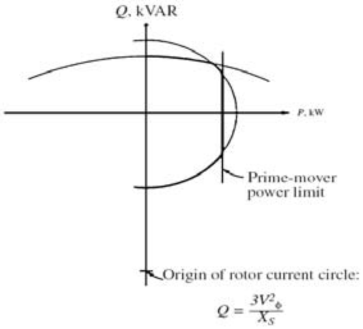


Fig. 7. A capability diagram showing the prime-mover power limit [24]

Listed below are the specifications for the Continuous Generating Unit Reactive Capability Curve:

- Following data for each point on the curve must be specified:
  a. The "Unit Net MW Output" provided to the system, as measured at the low-side of the unit step-up transformer, excluding any station service load fed of the unit terminal bus.
  b. The leading or lagging "Unit Minimum Net MVAR Limit" at the specified "Unit Net MW Output", as measured at the low side of the unit step-up transformer, excluding any station service load fed off of the unit terminal bus.
  c. The leading or lagging "Unit Maximum Net MVAR Limit" at the specified "Unit Net MW Output", as measured at the low side of the unit step-up transformer, excluding any station service load fed off of the unit terminal bus.
- The "Unit Minimum and Maximum Net MVAR Limits" must indicate the realistic, usable capability that is sustainable during continuous long-term unit operation. This sustainable continuous capability is based on actual operating experience (or testing) and takes into consideration any normal unit or plant restrictions at 95 degrees Fahrenheit ambient or above. Therefore, the reactive capability derived results in the proven sustainable reactive capability, rather than merely reflecting the design limits of the unit.
- A sufficient number of curve points must be provided to accurately model the full operating range and

capability of the unit as described above.

Data requirements:

- A minimum of two curve points must be provided.
- A maximum of eight curve points may be provided.
- The “Unit Maximum Net MVAR Limit” must be greater than (or equal to) the “Unit Minimum Net MVAR Limit” for each curve point.
- The “Unit Minimum Net MVAR Limit” may be equal for any number of adjacent curve points.
- The “Unit Maximum Net MVAR Limit” may be equal for any number of adjacent curve points.
- The “Unit Net MW Output” must be increasing from the first to the last point.

More information is available in reference [18] with detailed Explanation. Although the direct method provides exact RCC of the synchronous generators, but has disadvantages:

- Coordination is required between System Control Center personnel, power plant personnel and the General Office engineering group coordinating the testing.
- Sufficient system generating capacity is needed to accommodate the partial loss of generation due to running the unit being tested at minimum load.
- This testing can be costly as the unit under test is removed from the normal order of economic dispatch.

Test requires switching of electrical auxiliary equipment in the power plant.

IV.2. Indirect Method

As mentioned, the exact direct method is expensive and time consuming and it is preferred that the capability curve to be obtained using simpler and cheaper methods. In [13], [20] new and indirect methods are presented to acquire reactive capability curve of the synchronous generators indirectly using historical data of the plants and on-line conditions of the generator. Provided methods are capable to acquire the capability curve in real-time without any need to especial test conditions. In addition, proposed programs collect data when generator is operating at a number of operation load levels and a number of different power factors to require information regarding the real and reactive power generated at each of the various operating load levels and power factors. Subsequently, the proposed method analyzes the collected data to determine an actual reactive capability curve of the generator.

The system also provides generator health monitoring and identifies changes and trends in the capability curves of the generator.

Any power plant can be considered in indirect method, in [13], [20] combined cycle power plants are considered. Fig. 8 shows schematic diagram of such power plant.

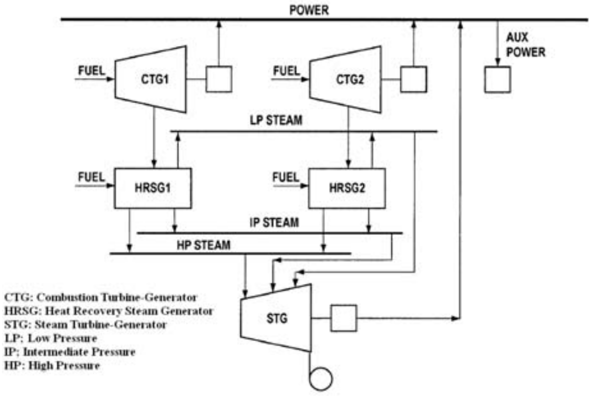


Fig. 8. Schenmatic diagram of a combined cycle power plant [20]

To evaluate real and RCC of the generator, it is assumed that the output real and reactive power of units is functions of the input variables of the power plant. For this purpose, the combustion and steam units of a combined cycle power station are considered separately. Therefore, the reactive output of the combustion units is taken as a function of the heat into unit from the fuel, compressor inlet temperature, cold gas generator temperature, cold gas generator pressure and power factor. Similarly, the real power is another function of the mentioned parameters. Also for the steam units the reactive power is taken as a function of amount of high pressure steam from heat recovery steam generator, amount of hot reheat steam from heat recovery steam generator, amount of low pressure steam from heat recovery steam generator, cold gas generator temperature, cold gas generator pressure and power factor. For the real power, the similar function is taken. It is available to write these functions briefly for combustion units:

Q = f(heat into unit from the fuel, compressor inlet temperature, cold gas generator temperature, cold gas generator pressure and power factor)

P = f(heat into unit from the fuel, compressor inlet temperature, cold gas generator temperature, cold gas generator pressure and power factor)

In addition, for steam units:

Q = f(amount of high pressure steam, amount of hot reheat steam, amount of low pressure steam, cold gas generator temperature, cold gas generator pressure and power factor)

P = f(amount of high pressure steam, amount of hot reheat steam, amount of low pressure steam, cold gas generator temperature, cold gas generator pressure and power factor)

Because of the relation between the mentioned parameters and reactive and real power is non-linear so it is difficult to determine a simple function. In these cases, it is proposed to use techniques such as neural networks, evolutionary algorithms such as genetic algorithm, curve fitting with interpolation, regression etc to find the best approximation to the non-linear function. In [20] neural-networks technique is chosen to approximate the relationship between output power and input parameters. Fig. 9 presents a schematic diagram of the neural-network used to approximate the relation between output reactive power and input parameters in the combustion units is presented.

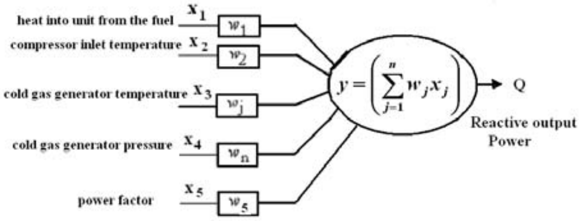


Fig. 9. Schematic diagram of the neural-network used to approximate the relation between output reactive power and input parameters in the combustion units

In addition, for active power in combustion units also for reactive and real power output in steam units, similar configuration of the neural-networks is used which for abbreviation are not presented here. When the relation between output power and input parameters is determined, it is possible to estimate real and reactive power in any given conditions. Therefore, it is possible to obtain new capability curves of the synchronous generator. Fig. 10 presents an estimated capability curves using indirect method.

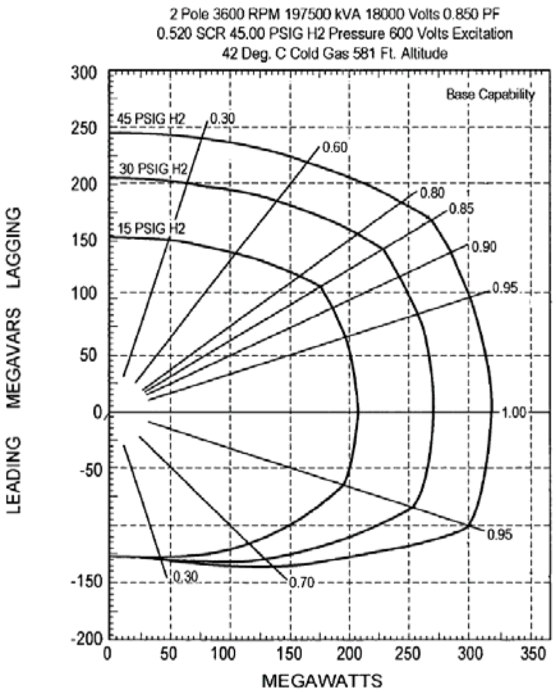


Fig. 10. Estimated RCC [20]

V. Conclusion

In this paper, a new challenge for participant in the reactive power market is discussed. In majority of the applications and in active and reactive power dispatch programs, it is assumed that the capability curves of the generators are fixed; therefore, the curves provided by manufacture of the generators are used. Nevertheless, as discussed in this paper, RCC of the generators is changed over time. Therefore, it is essential to re-check the generator in order to obtain new and updated capability curves. In recent papers, RCC re-evaluation is reported for voltage coordination, economic dispatch, reliability improvement, proper setting for excitation controller and generator protection. In reactive power market been shown that re-evaluation of RCC is essential for participation. It is shown that updated RCC not only limits the reactive capability production, but also improves reactive power boundaries and the profit of power plant owners will be increased.

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Authors' information

[1]Faculty of Engineering, Ferdowsi University,Mashhad, Iran.
[2]Khorasan Regional Electrical Company, Mashhad, Iran.

Ismail Niazy was born in Mashhad, Iran on May 16, 1983. He received the B.Sc. in electrical engineering from Ferdowsi University of Mashhad, Mashhad, Iran 2006. Since 2007 he has been studding toward M.Sc. degree in Ferdowsi University of Mashhad, Iran. His research interests are power system protection, fault location and power generation.

Hashem Mortazavi was born in Bojnord , Iran on 1974. He received his B.Sc degree in Electrical Engineering from Ferdowsi University of Mashhad in 1998, Tehran , Iran and M.Sc degree with honor in Electrical Engineering from Ferdowsi University in 2001, Mashhad , Iran . Presently, he is a Senior Electric Supervisor in Krec, Mashhad , Iran . His research interests are Generator protection, Smart Grid and Renewable energy Integration.

Jaafar Ebadi was born in Mashhad, Iran on 1962. He received the B.Sc. and M.Sc. degrees in electrical engineering both from Ferdowsi University of Mashhad, Mashhad, Iran on 1987 and 1991, respectively. Since 1992 he served as an professor at the Ferdowsi University of Mashhad. His research interests are electric machinery, power plant and power generation.

Soheil Sabzevari was born in Sabzevar, Iran on October 3, 1983. He received the B.Sc. in electrical engineering from Ferdowsi University of Mashhad, Mashhad, Iran 2006. Since 2007 he has been studding toward M.Sc. degree in Ferdowsi University of Mashhad, Iran. His research interests are power market, electrical railway systems and power generation.

Abraham Niazy was born in Mashhad, Iran on May 16, 1983. He received the B.Sc. in electrical engineering from Ferdowsi University of Mashhad, Mashhad, Iran 2007. His research interests are low consumption lamps and power generation.