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Full Length Research Paper

Photoluminescence from GaAs nanostructures

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The confinement properties of semiconductor nanostructures have promising potential in technological application. The main objective of this study is to describe the dependence of Photoluminescence (PL) intensity on different parameters like temperature, excitation wavelength, time and photon energy of GaAs quantum dots (QDs). The model equations are numerically analyzed and simulated with matlab and FORTRAN codes. The experimental fitted values and physical properties of materials are used as data source for our simulation. The result shows that at low temperature the peak is quite sharp, as temperature increases the PL intensity decreases and get quenched at particular thermal energy.

Key words: Photoluminescence (PL) intensity, GaAs quantum dots, nanostructures, quantum confinement, thermal quenching energy.

INTRODUCTION

Nanomaterials are the cornerstones of nanoscience and nanotechnology and are anticipated to play an important role in future economy, technology, and human life in general. The strong interests in nanomaterials stem from their unique physical and chemical properties and functionalities that often differ significantly from their corresponding bulk counterparts. Exceptionally large surface area to volume ratios relative to the bulk produces variations in surface state populations that have numerous consequences on material properties (Jin and Christian, 2007).

The small size of nanostructures permits the infamous electronic device scaling for faster operation, lower cost and reduced power consumption. These unique properties enable the variety of electronic, photonic and optoelectronic information storage, communication, energy conversion, catalysis, environmental protection, and space exploration applications based on semiconductor nanostructures (Alivisatos, 1996).

Semiconductor nanoparticles, generally considered to be particles of material with diameters in the range of 1 to 10 nm (Pan and Feng, 2008).

GaAs has advantages in electronic properties which are superior to those of silicon. It has a higher saturated electron velocity and higher electron mobility, allowing transistors made from it to function at frequencies in excess of 250 GHz. Unlike silicon junctions, GaAs devices are relatively insensitive to heat owing to their wider band gap. It tends to have less noise than silicon devices especially at high frequencies. Because of its wide direct band gap transition, GaAs is an excellent material for space electronics and optical windows in high power applications. Combined with the high dielectric constant, this property makes GaAs a very good electrical substrate and unlike Si provides natural isolation between devices and circuits (Blakemore, 1982).

Photoluminescence (PL) is the spontaneous emission of light from a material under optical excitation. The

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excitation energy and intensity are chosen to probe different regions and excitation concentrations in the sample. PL investigations can be used to characterize a variety of material parameters. PL spectroscopy provides electrical characterization; it is selective and extremely sensitive probe of discrete electronic states.

Intensity of the PL signal has received the most attention in the analysis of interfaces. This interest is due to the fact that, although several important mechanisms affect the PL response, it is generally found that large PL signals correlate with good interface properties (Timothy, 2000).

Dependence of PL intensity on different parameters

Temperature dependence of PL emission

The overall shift of the QD emission to lower energies is caused by band gap narrowing. At low temperature ($T < 100\text{K}$) the carriers are captured by the QDs randomly. Once captured, the carriers in the QDs cannot be thermally excited (Teo et al., 1998). So the emission reflects the normal distribution of the QD. Irrespective of the specific quenching mechanism, the temperature dependence PL intensity for GaAs nanostructures with intensity near absolute zero I_0 , rate parameter C and activation energy E_t is given by Kittel (2005):

$$I(T) = \frac{I_0}{1 + C \exp\left(\frac{-E_t}{k_B T}\right)} \quad (1)$$

This equation is used to simulate data on the dependence of PL intensity on temperature.

Optical absorption

The absorption coefficient α describes how the light intensity is attenuated on passing through the material. The intensity transmitted through the sample of thickness z with incident light intensity I_0 is given by:

$$I(z) = I_0 \exp(-\alpha z) \quad (2)$$

The quantum confinement model

The low-temperature PL spectrum of the GaAs QD ensembles shows a Gaussian profile with a line width broadening of 30nm (Jung et al., 2004).

The photon energy emitted would be slightly larger than the band gap energy (Sze and Kwok, 2007):

$$h\nu = \hbar\omega = E = E_c + \frac{\hbar^2 k^2}{2m_e^*} - \left(E_v - \frac{\hbar^2 k^2}{2m_h^*} \right) = E_g + \frac{\hbar^2 k^2}{2m_r^*} \quad (3)$$

According to the Quantum Confinement (QC) model, the emission wavelength and intensity depend on nanocrystal diameter, size distribution and concentration. This model can explain the general tendency of most experimental results such as the blue shift of the luminescence spectrum with decrease of the GaAs-nanocluster size.

Weak confinement

The electrons and holes can now be thought of as independent particles; excitons are not formed. Separate quantization of motion of the electron and hole is now important factor. The optical spectra should consist of a series of lines due to transitions between sub bands. The shift in energy is now:

$$\Delta E = \frac{\hbar^2 \pi^2}{2\mu R^2} \quad (4)$$

Strong confinement

When the excitonic mass is replaced by the reduced mass μ in the weak confinement regime the dominant energy term is the Coulomb term, and quantization of the motion of the exciton occurs. The shift in energy of the lowest energy state is:

$$\Delta E = \frac{\hbar^2 \pi^2}{2m_e^* R^2} \quad (5)$$

Where, $\frac{1}{M} = \frac{1}{m_e^*} + \frac{1}{m_h^*}$

Assuming that a Gaussian size distribution about the mean diameter d_0 for the nanocrystallites (Mic'ic' et al., 1997):

$$I(d) = N \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(d-d_0)^2}{2\sigma^2}\right) \quad (6)$$

The number of electrons N in a column diameter d participating in the PL process is proportional to d^2 .

Dependence of PL intensity on time

Photoluminescence experimental samples are excited with ultra-short light pulses and the change of the emitted light as a function of time is observed (Lingmin et al., 2009).

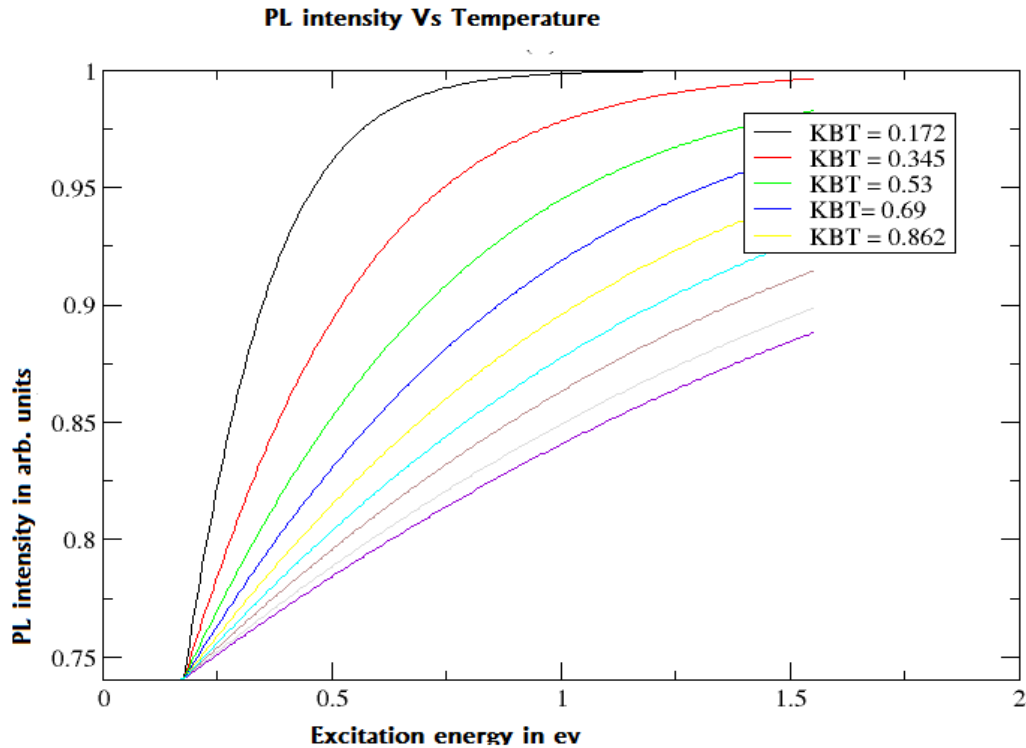


Figure 1. PL intensity versus thermal energy for GaAs nanostructures.

To gain information about the carrier dynamics is necessary to find the relationship between the photoluminescence decay and the carrier lifetimes. The photoluminescence intensity, that is, the light signal emitted by the material due to radiative recombination, is proportional to the product of electron and hole concentrations (GhodsNahri et al., 2010):

$$I(t) = I_0 \exp\left(\frac{-t}{\tau}\right)^\beta \tag{7}$$

Where $I(t)$ and I_0 are the PL intensity as a function of time and at $t = 0$, respectively, τ is the PL decay time constant, and β is a dispersion factor ≤ 1 . Thus, the capture rates can be extracted from PL transients if either the radiative recombination rate is known or at least much smaller than the capture rate. However it is not possible to distinguish between the influences of electron and hole capture (GhodsNahri et al., 2010).

METHODOLOGY

In this work problems are solved analytically and numerical techniques had been used to determine the most important optical parameter for PL intensity. In order to obtain the desired result for this work we have simulated data using matalab codes for temperature and time dependent intensity. We assumed Gaussian model equation that describes the dependence of PL intensity on

the size of the nanocluster and matlab Fortran 90 program have been developed for the model equation that simulates the data to compare with experimental results. The results obtained with this simulated data with the model equation agree with experimental results done by other researchers.

RESULT AND DISCUSSION

PL intensity versus temperature

Figure 1 depicts the PL intensity as a function of thermal energy for temperatures ($T = 20k, 40k, 60k, 80k, 100k, 120k, 140k, 160k, 180k$ and $E_a = 0.08 eV$) fitting parameters are involved. This simulation result is in good agreement with experimental results; the emission spectra for GaAs show that PL intensity very high at low thermal energy. The activation energy is about 0.25 eV. Due to the increasing temperature the thermal energy increase at which 1.5 eV PL gets quenched, thus 1.5 eV is quenching thermal energy.

PL intensity versus wavelength

Figure 2 shows the PL intensity as a function of wavelength for GaAs nanostructures. For both values of

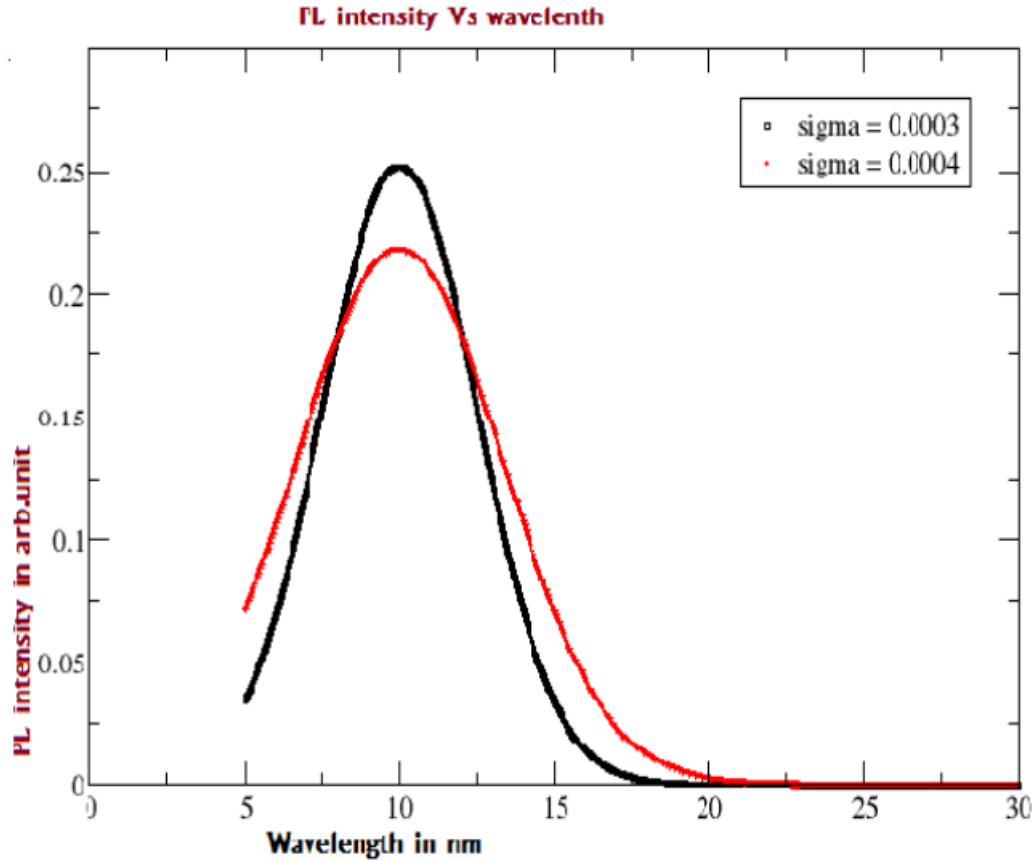


Figure 2. PL intensity versus wavelength.

the standard deviation σ , the PL intensity has sharper peak when near the center of the Gaussian curve. Semiconductors are transparent to photons whose energies lie below their band gap and are strongly absorbing for photons whose energies exceed the band gap energy (Ardyanian and Ketabi, 2011). The simulation result shows that the PL intensity decreases as the wavelength increases to a certain peak and then decreases continuously.

PL intensity versus photon energy

Figure 3 depicts the simulation result of PL intensity versus Photon energy for GaAs nanostructures. The photo flux absorbed by semiconductor nanostructures enforces the material's property got to be changed from one phase to other. The excitation of electron-hole changed to tunneling of electron from valance band to conduction band.

PL intensity versus time

Figure 4 shows the simulated result of PL intensity versus

time (a) and the experimental result carried out by other researchers (b) from literature (Jong, 2009) for comparison. It is observed that as decay life time increases the PL intensity decreases.

The PL decay time of GaAs nanostructures decreases monotonically with increasing time. A shorter decay time constant allows a higher modulation frequency, but reduces the efficiency. This is due to the decrease in oscillation period and resulting non radiative recombination of the particles in the nanocrystal.

Conclusion

The emission spectra of GaAs QD show that there is high PL intensity at low temperature. As the temperature increases, the thermal energy increases and the PL gets quenched. The result also shows that PL intensity decrease as wavelength increases. Sharp peak PL intensity is observed near the mean diameter of GaAs QD. PL intensity observed between limited visible photon energy. As photon energy increased exceeding energy gap the peak PL intensity become lowered. The PL intensity decays with time; this is because of the contributions of radiative and non-radiative transitions.

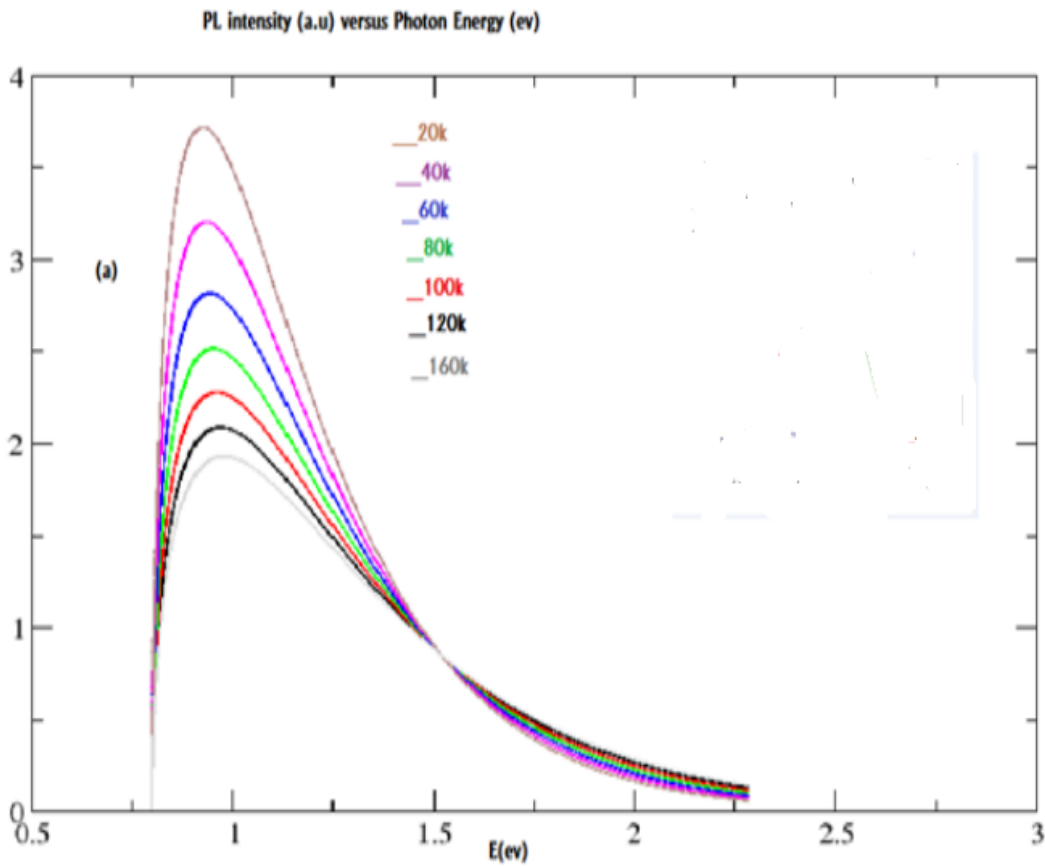


Figure 3. PL intensity Vs. photon energy.

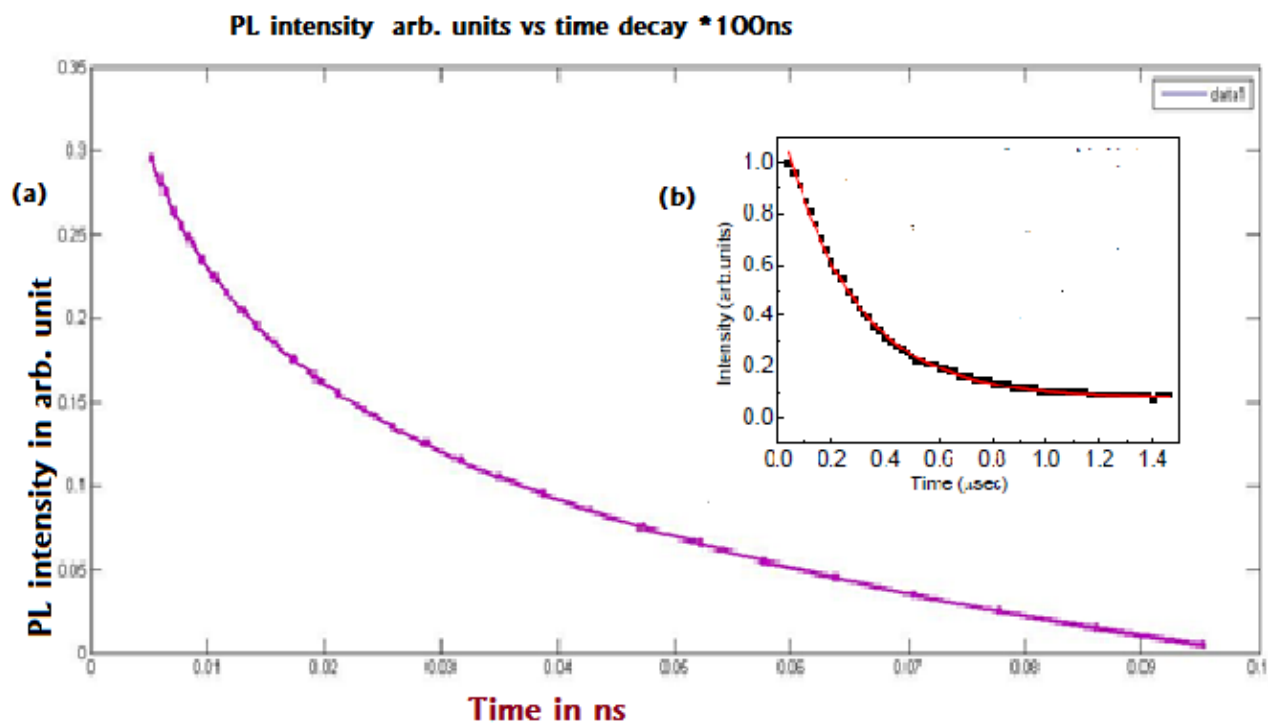


Figure 4. PL intensity vs. decay time.

Conflict of Interest

The authors have not declared any conflict of interest.

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Full Length Research Paper

Relation between classical mechanics and physics of condensed medium

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An equilibrium system of potentially interacting material points in a nonhomogeneous field is studied by numerical simulations, as well as criteria which are needed in order to switch from the quantified model to the thermodynamic one. This paper studies the system passing a potential barrier and factors which affect the change of the system's internal energy. These factors include width of the barrier, number of material points in the system, as well as initial conditions. The dependence between change in fluctuations of energy parameters of the system and the number of material points is also shown. The amount of dynamic entropy is estimated. The paper also defines and describes two critical values (N1 and N2). If the system includes more than N1 material points, then its dynamics becomes irreversible. If the number of material points is greater than N2, then thermodynamic model can be used. The results obtained by numerical simulations verified the theoretical conclusions.

Key words: Nonlinearity, classical mechanics, energy, thermodynamics, Lagrange equations, non-holonomic constraints, irreversibility.

INTRODUCTION

The possibility to derive the laws of thermodynamics, statistical physics and kinetics using the laws of classical mechanics is still considered as an open question. First of all, this is due to the fact that in the nature all processes are irreversible and dissipative. However, in accordance to the formalism of classical mechanics, the dynamics of systems are reversible. It is subject of one of the key problems of physics (Ginzburg, 2007; Bohr, 1958; Klein, 1961; Prigogine, 1980; Lebowitz, 1999; Zaslavsky, 1984). Up to the present time, clear criteria for the transition to the physics of continuous media are not set. For example, it is not possible to determine the exact number of elements a system should consist of, in order to become thermodynamically applicable, as well as the

accuracy of any estimation which is done using the laws of thermodynamics. The abovementioned problems are not solved yet since until recently there was no rigorous explanation of irreversibility in the framework of the laws of classical mechanics, without introducing probabilistic hypotheses (Prigogine, 1980; Lebowitz, 1999; Zaslavsky, 1984; Smoluchowski, 1967; Cohen, 1998; Klimontovich, 1995; Kadomtsev, 1995; Sidharth, 2008). Indeed, today irreversibility is usually explained by the property of exponential instability of Hamiltonian systems and the hypothesis of the existence of fluctuations. The main idea of this explanation is as follows. According to the Poincare theorem on the reversibility of Hamiltonian systems, a system's coordinates in the phase space will

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be close enough to their initial values in a finite (although it can be very large) period of time (Prigogine, 1980; Zaslavsky, 1984; Smoluchowski, 1967). But if averaged over an arbitrarily small neighborhood of the phase space, the system will not return back to its initial position because of exponential instability. Arbitrarily small fluctuations in the system are equivalent to such averaging. Therefore, the existence of fluctuations in Hamiltonian systems is a sufficient condition for the occurrence of irreversibility. But the hypothesis of a roughening of the phase space due to fluctuations actually involves statistical laws which are alien to determinism of classical mechanics. Therefore, the question of justifiability of this hypothesis is still open.

A lot of attempts to explain the second law of thermodynamics on the basis of the laws of classical mechanics without the use of statistical hypotheses failed, so most probably it is impossible to solve this problem in the framework of the existing formalism of classical mechanics (Prigogine, 1980; Zaslavsky, 1984). This means either that there is no explanation in the framework of classical mechanics at all or that the formalism of classical mechanics requires expansion, for example by removing the limitations under which it was built (Prigogine, 1980).

In order to find an approach to solve the problem of irreversibility the dynamics of a system of hard discs has been studied firstly. Unlike other authors who studied the system of billiards, provided that they are Hamiltonian systems (Bird, 1976; Sinai, 1995), we considered the billiards in the approach of pair collisions of disks (Somsikov et al., 1999; Somsikov, 2004). As a result the irreversibility of the system of hard disks was found. It turned out that the exchange of momentum between the discs plays a key role in irreversibility. The Hamilton's and Lowville's equations describing equilibration in a system were obtained basing on these results (Somsikov, 2004). But a number of problems still remained. For example, the pair interaction in a real system is a special case which is valid only for fairly rarefied systems. Moreover, the interactions between the system's elements are potential. Therefore, the next step was the study of systems of potentially interacting material points (Somsikov, 2005).

It followed from the study of systems of hard discs that the mechanism of irreversibility cannot rely on the formalism of classical mechanics. Therefore, it was decided to look for an answer based on the energy equation for systems of potentially interacting elements, provided that Newton's laws are valid for each individual material point. As a result of these studies it was found that the system's dynamics is irreversible. Irreversibility was caused by the mutual transformation between the system's motion energy and its internal energy (Somsikov, 2014). But one problem still remains unsolved: Why formalisms of classical mechanics are reversible, while the dynamics of systems of material

points is irreversible. This contradiction should be explained; it was found that in classical mechanics irreversibility has been lost while obtaining the Lagrange equations for systems of material points because of usage of the hypothesis of holonomic constraints (Somsikov, 2014). It turned out that this hypothesis excludes the possibility of describing the nonlinear transformation of energy between different degrees of freedom, which is responsible for the irreversibility.

It turned out that it is possible to explain irreversibility using Newton's laws by removing some of the limitations of classical mechanics formalism. The mechanics of structured particles (SP) was developed and a mechanism to explain irreversibility was offered. This mechanism was named deterministic as it uses the mechanics of SP without any probabilistic principles. The essence of this mechanism is as follows (Somsikov, 2014a; Somsikov, 2014b).

Newton built the mechanics for an abstract structureless material point (MP). Therefore, the external forces change only the position of MP. This fact defines Newton's second law. But all real bodies are not structure-less. Thus the external forces change not only the position of a body, but its internal energy as well. The internal energy is accounted for the motion of elements of the body with respect to its center of mass. This means that the dynamics of the system is defined by the principle of dualism of symmetry due to the fact that the system is not structure-less. The essence of the principle is that the dynamics of real bodies is determined by two types of symmetry: The symmetry of space and the symmetry of the body itself. The principle of dualism of energy follows from the principle of dualism of symmetry. The principle of dualism of energy claims that the dynamics of a real body is defined by splitting the body's total energy into its internal energy and the energy of motion. The equation of the body's motion follows from the principle of dualism of energy. This equation takes into account both the work needed to change the position of the body, and the work than changes the body's internal energy (Somsikov, 2014b).

Thus, the total energy of the body is an invariant which determines the body's dynamics; the energy of motion itself is not an invariant, so the motion of the body's mass center should be determined based on the invariance of the total energy.

According to classical mechanics, a body can be represented by a set of potentially interacting MPs (Goldstein, 1975; Landau, 1976). This means that the equation of motion of the body should be derived upon the condition that the motion of each MP is described by the laws of Newton. In general a body is an open non-equilibrium dynamic system. Such system in many cases could be considered as it is in a local thermodynamic equilibrium state (Klimontovich, 1995; Landau, 1976; Rumer and Rivkin, 1977). In this case, the body can be represented by a set of moving equilibrium subsystems;

each subsystem is in turn a set of potentially interacting MPs (Landau, 1976; Rumer and Rivkin, 1977). Let us name such a subsystem as a structured particle (SP). This means that the dynamics of an open non-equilibrium system should be defined based on the assumption that the system consists from a lot of SPs. Therefore, first of all, the mechanics of SPs should be built in order to describe the dynamics of real bodies.

As it turned out, the equation of motion of a SP allows explaining the mechanism of irreversibility without the use of probabilistic hypothesis of fluctuations (Somsikov, 2014a; Somsikov, 2014b). This is because the energy of motion is no longer an invariant for a SP, as it was for a MP. It has been found that the energy of the SP's motion is transformed into its internal energy in the non-homogeneous field of external forces. Increase in the internal energy is proportional to the gradient of the external forces. If the external field is weak enough, then the SP remains in equilibrium along its path. At the same time its internal energy can increase only, but it cannot be transformed into the energy of motion. This is the essence of deterministic irreversibility that is such irreversibility which follows from the deterministic laws of classical mechanics; unlike the irreversibility explained within the canonical framework of classical mechanics (Prigogine, 1980; Zaslavsky, 1984), the deterministic irreversibility does not need the hypothesis of fluctuations. Thus, the deterministic mechanism of irreversibility is caused by transformation of energy of a system's motion into its internal energy when the system is in a non-homogeneous field. The fact that in this case the energy of motion is not constant means that the time symmetry is broken. However, the sum of the energy of motion and the internal energy is constant. Hence it is clear that in order to explain the nature of deterministic irreversibility for a non-equilibrium system, the following should be done:

1. Represent a non-equilibrium system by a set of moving relative to each other equilibrium subsystems.
2. Represent the energy of these subsystems as the internal energy and the energy of motion.
3. Obtain the equation of motion of subsystems directly from the dual form of energy, thus preserving the nonlinear terms which are responsible for energy exchange different degrees of freedom.

Unlike the deterministic mechanism of irreversibility, the traditional statistical mechanism refers irreversibly in Hamiltonian systems to the hypothesis of the existence of arbitrarily small fluctuations. The point is that since the Hamiltonian systems are exponentially unstable, then the presence of such fluctuations results in irreversible dynamics. The presence of fluctuations in these systems or in the external limitations is a sufficient condition for the irreversibility.

The deterministic irreversibility is a strong argument in

favor of determinism of nature. This is very important; just recall the fundamental debates of Bohr and Einstein's on determinism and randomness, which took place during creation of quantum mechanics (Ginzburg, 2007; Bohr, 1958;).

Due to the dualism of energy, the equation of a SP's motion is given by independent micro and macro variables. Moreover, micro variables define the motion of the MPs relative to the center of mass of the SP, while macro variables define the motion of the SP's center of mass itself. Deriving equation of motion of the SP in this way takes into account possible transformation of the energy of the SP's motion into its internal energy and requires no use of the hypothesis of holonomic constraints, which is the basis for deriving the canonical equation of Lagrange. Unlike the canonical equation of Lagrange, the equation of the SP's dynamics describes the nonlinear transformation of the SP's motion energy into its internal energy; this transformation breaks the symmetry of time (Somsikov, 2014a).

An oscillator passing through a potential barrier was studied, and it was found that the condition of holonomic constraints eliminates nonlinear terms in the equation, which are responsible for breaking of time symmetry (Somsikov and Denisenya, 2013). This issue is considered in more detail subsequently.

Existence of deterministic irreversibility leads to the concept of "deterministic entropy" (D-entropy) (Somsikov, 2014a; Somsikov, 2014b). D-entropy is a deterministic one, because it strictly follows from the laws of classical mechanics without use of the hypothesis of fluctuations in a system. It is defined as the relative change in the system's internal energy. Unlike the thermodynamic entropy, D-entropy for a system consisting of small number of MPs can be both positive and negative.

The equation of the SP's motion is nonlinear. It is almost impossible to do any analytical analysis in order to check the theoretical conclusions following from the equation. Hence numerical simulations are the only way to check the theoretical conclusions. Numerical simulations allow determining the criteria for switching from classical mechanics to thermodynamics, statistical physics, kinetics, as well as identifying the cases when the system is irreversible, depending on the properties of the system, etc.

So, the objective of the paper is to determine the basic dynamic properties of a system of potentially interacting MPs in a non-homogeneous external field using numerical simulations. The estimation of fluctuations of the system's internal energy depending on the number of MPs, as well as initial parameters of the system and the barrier has been done, dependence of change in the system's internal energy on the barrier's width, as well as D-entropy have been studied. This study made it possible to verify the theoretical conclusions about the dynamics of a SP, define the criteria needed to switch from the deterministic to the thermodynamic model for a system.

In addition, it made it possible to show how the important statistical laws of physics may result from the strict laws of classical mechanics, as well as define some cases when the mechanism of irreversibility is applicable.

AN OSCILLATOR PASSING A POTENTIAL BARRIER

Initially, the simplest system, more specifically a one-dimensional oscillator of two MPs connected by a spring, has been considered (Somsikov and Denisenya, 2013). The oscillator's total energy includes the energy of motion and the internal energy. These two types of energy are given in the independent micro and macro variables. Micro variables describe the oscillations, while macro variables determine the motion of the oscillator's mass center.

It was found that the presence of a non-homogeneous external field made the micro and macro variables dependent. As a result, mutual nonlinear transformation of the energy of motion into the internal energy was taken into account. This nonlinear transformation was lost when deriving the Lagrange equation because of use of the hypothesis of holonomic constraints (Somsikov, 2014b). This means that it is impossible to obtain the effects resulting from a nonlinear relation between the degrees of freedom within the formalism of Lagrange.

Let us explain on an example of two-body problem, how the uses of the hypothesis of holonomic constraints excludes the possibility of describing the energy exchange between different degrees of freedom. There are two ways of obtaining the motion equations of a system of two MPs. The first way is a traditional one. The motion equation for two MPs in the external field is given by Sinai (1995):

$$\dot{\mathbf{v}}_1 = -F_{12} - F_1^0; \dot{\mathbf{v}}_2 = -F_{21} - F_2^0 \quad (1)$$

Here F_1^0, F_2^0 are the external forces, acted on a first and second MP; F_{12} is the force of interaction of MPs

Let us add and subtract these equations. As a result, we obtain:

$$\dot{\mathbf{v}}_1 + \dot{\mathbf{v}}_2 = -(F_1^0 + F_2^0); \dot{\mathbf{v}}_1 - \dot{\mathbf{v}}_2 = -2F_{12} - F_{12}^0 \quad (2)$$

Where $F_{12}^0 = F_1^0 - F_2^0$

Equation (2) can be rewritten as:

$$2\dot{V} = -(F_1^0 + F_2^0); \dot{\mathbf{v}}_{12} = -2F_{12} - F_{12}^0 \quad (3)$$

Where $V = \frac{1}{2} (\sum_{i=1}^2 \mathbf{v}_i)$; $\mathbf{v}_{12} = \mathbf{v}_1 - \mathbf{v}_2$

Thus, according to the Equation (3), the motion of the system in the external field is an independent motion of the system's center of mass and the relative motion of MPs. The motion of the center of mass is defined by the sum of the external forces applied to it. Relative motion of

MPs is determined by their interaction forces and the difference between the external forces acting on each MP. According to these equations, there are two invariant of motion. The first invariant is the energy of motion of the system as a whole, and the second invariant is the energy of the relative motion of MPs.

Now consider the derivation of the motion equation for a system basing on the energy equation. By differentiating the system's energy with respect to time, we get:

$$\mathbf{v}_1 (\dot{\mathbf{v}}_1 + F_{12} + F_1^0) + \mathbf{v}_2 (\dot{\mathbf{v}}_2 + F_{21} + F_2^0) = 0 \quad (4)$$

In general case the variables in Equation (4) cannot be separated. The sum is equal to zero not only when each term is equal to zero (as it is postulated by the hypothesis of holonomic constraints), but each term itself could be different from zero while their sum is zero. By regrouping the terms of equation (4), we obtain:

$$(\mathbf{v}_1 \dot{\mathbf{v}}_1 + \mathbf{v}_2 \dot{\mathbf{v}}_2) = -F_{12} \mathbf{v}_{12} - \mathbf{v}_1 F_1^0 - \mathbf{v}_2 F_2^0 \quad (5)$$

By comparing this equation to Equation (3), using as the variables the velocity of the mass center and the relative velocities of MPs, the result obtained is:

$$2V\dot{V} + \frac{1}{2} \mathbf{v}_{12} \dot{\mathbf{v}}_{12} = -V(F_1^0 + F_2^0) - \frac{\mathbf{v}_{12}}{2} (F_{12} + F_{12}^0) \quad (6)$$

It is equivalent to the following equation:

$$V[2\dot{V} + (F_1^0 + F_2^0)] + \frac{\mathbf{v}_{12}}{2} [\dot{\mathbf{v}}_{12} + 2F_{12} + F_{12}^0] \quad (7)$$

The terms in Equation (6) are grouped so that the first term determines the motion of the mass center, while the second term determines the change in the internal energy.

Equation (6) is equal to Equation (3) in the next cases: When $F_{12}^0 = 0$, when $\mathbf{v}_{12} = 0$, and when external forces are linear. The first case is equivalent to the rigid connection between the MPs. The second case is equivalent to the homogeneity of the external field. The third case is associated with a linear dependence of external forces on the coordinates. Only in these cases the variables are separated. In general case of a non-homogeneous external field the variables of the Equation (6) cannot be separated and the hypothesis of holonomic constraints is not valid, that is, Equations (3) and (6) are not equivalent. Numerical simulations of an oscillator in a non-homogenous field have confirmed this conclusion (Somsikov, 2014b).

As it turned out, in some cases the oscillator can pass the potential barrier even if its energy of motion is less than the height of the barrier (Figure 1).

In some cases the oscillator can also reflect, even if its

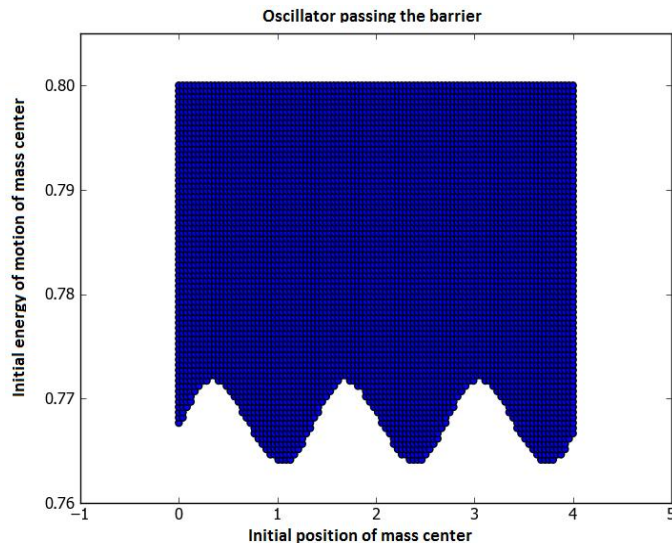


Figure 1. The filled area corresponds to the cases when the oscillator passes the barrier (depending on its initial energy of motion and phase).

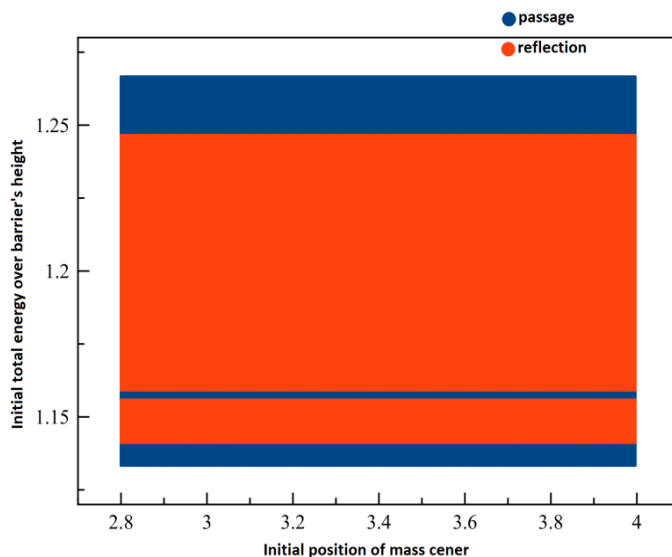


Figure 2. Oscillator's reflection / passage areas depending on its initial energy and position (red fill corresponds to reflection).

energy of motion is greater than the height of the barrier. Moreover, while gradually change the initial phase, it is possible to get interchangeable areas where the oscillator passes the barrier and where it is reflected (Somsikov and Denisenya, 2013) (Figure 2). These effects disappear if one neglects the nonholonomic constraints, that is, excludes consideration of the nonlinear mutual transformation of the oscillator's energy of motion into its internal energy.

At the moment when the oscillator is near the potential barrier, it is its phase that determines the sign of change

in the internal energy (Figure 3). The result also depends on the height of the barrier, the oscillator's energy of motion, and other parameters. Thus, the calculation of oscillator's motion shows the important role of nonlinear effects in the dynamics of a system in a non-homogeneous field. These nonlinear effects can be studied only by using the principle of duality of symmetries, taking into account the transformation of the system's energy of motion into the energy of motion of the MPs relative to the system's center of mass.

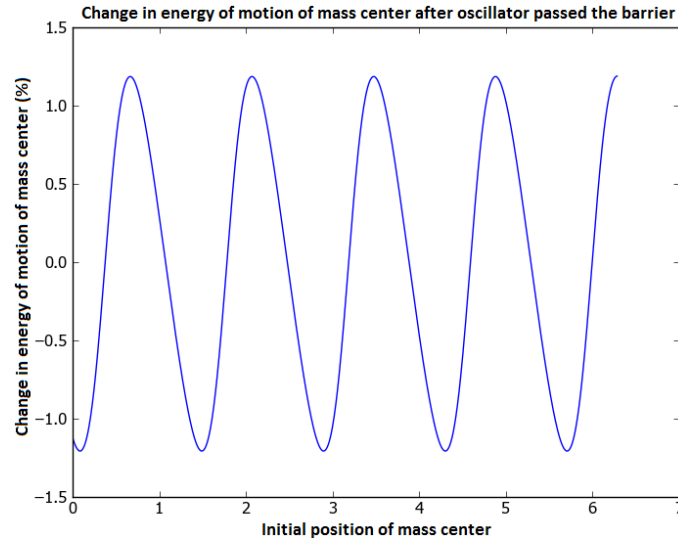


Figure 3. Change in the oscillator's energy of motion (% of its initial value) depending on its initial phase.

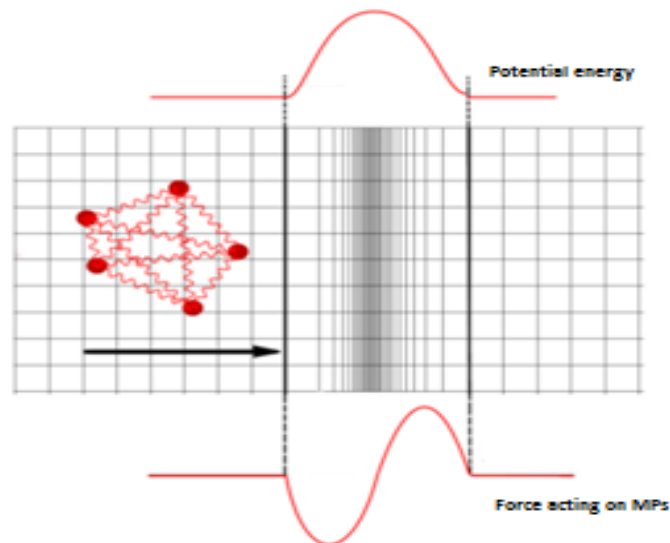


Figure 4. The scheme of numerical simulations of the system passing the potential barrier.

FORMULATION OF THE PROBLEM OF A SYSTEM PASSING A POTENTIAL BARRIER

A system of potentially interacting MPs in a nonhomogenous field has been considered (Figure 4). The initial parameters include the system's internal energy and the energy of motion of its center of mass. Coordinates and velocities of the MPs were set randomly. Their sums are equal to zero in the center of mass. The system is represented by a ball with a certain radius at which the potential energy of interaction of the MPs is

equal to the total kinetic energy of the MPs.

The dual system of coordinates is used, that is the independent variables are the micro and macro variables. Microvariables determine the motion of each MP in the center of mass, while macro variables determine the motion of the center of mass itself. The barrier's height is chosen so that the system passes through it. Change in the system's internal energy, the system's motion energy, as well as D-entropy and other parameters of the problem are computed; the independent parameters include the number of MPs, the barrier's height and width,

as well as the initial conditions. The results obtained are compared with the statistical laws and with the theoretical conclusions obtained on the basis of the equations of motion of a SP (Somsikov, 2014a; Somsikov, 2014b):

$$M_N \dot{\vec{V}}_N = -\vec{F}^{env} - \frac{(\Phi^{env} + E_N^{ins}) \vec{V}_N}{V_N^2} \quad (8)$$

Where $\vec{V}_N = \dot{\vec{R}}_N$ is velocity of the center of mass, $i = 1, 2, 3, \dots, N$ - MP's count, $\vec{R}_N = \frac{1}{N} \sum_{i=1}^N \vec{r}_i$, $M_N = Nm$; $\vec{F}^{env} = \sum F_i^{env}(R_N, \vec{r}_i)$, $\dot{E}_N^{ins} = \sum_{i=1}^N \tilde{v}_i (m\dot{\vec{v}}_i + F(\vec{r}_i)_i)$ - change in the system's internal energy, $\Phi^{env} = \sum \tilde{v}_i F_i^{env}(R_N, \vec{r}_i)$, $\vec{F}_i^{env}(R_N, \vec{r}_i)$ - external force acting on i^{th} MP, $r_i = R_N + \tilde{r}_i$, \tilde{r}_i - MP's coordinates relative to the center of mass.

MPs interaction forces are given by Hooke's law. The external field is specified in the form of one period of a cosine $U(x_i) = U_b [\cos(2\pi(x_i - R_b)/a) + 1]$, provided $(R_b - \frac{a}{2}) < x_i < (R_b + \frac{a}{2})$. Hence the forces acting on each MP are given by:

$$F_i(x_i) = U_b \sin(2\pi(x_i - R_b)/a) \quad (9)$$

Where U_b is the barrier's height; R_b is the position of the barrier's max height; a is the barrier's width; x_i is the distance between i^{th} MP and the center of mass; i - MP's count. According to Equation (9), the force is proportional to the barrier's height, and inversely proportional to its width.

The numerical simulations are done for various initial distributions of MPs and parameters of the problem in order to determine the nature of the changes in the energy of motion and the internal energy of the system, depending on the number of MPs and initial parameters.

CHANGE IN THE SYSTEM'S INTERNAL ENERGY AS A FUNCTION OF THE INITIAL PARAMETERS AND THE NUMBER OF MPS

According to the theoretical results, the dynamics of a conservative nonequilibrium system, represented by a set of equilibrium subsystems in a nonhomogeneous external field, should be irreversible due to the transformation of the system's kinetic energy into its internal energy (Somsikov, 2014b). A similar conclusion follows from the statistical methods of analysis of nonequilibrium systems (Landau, 1976; Rumer and Rivkin, 1977). Let us consider how much MPs a system should consist of in order to be described in terms of empirical equations of thermodynamics and statistical laws.

If the theoretical results derived from the equations of

motion of systems are valid, then the numerical simulations should reveal that there is a certain number of MPs a system should consist of, such that the system's internal energy can increase only. This number ($N1$) can be taken as a first criterion for the system to be equilibrium. Obviously, this number should depend on the relative values of the internal energy, the energy of motion of the system, the potential barrier's height. Simulations have been done in order to verify existence of $N1$ and study its behavior depending on the parameters of the system; the simulations estimated the change in the system's internal energy depending on the number of MPs.

Figure 5 shows the results of 400 experiments for different number of MPs. Number of MPs correspond to a power of two (4, 8, 16, 32, 64, 128, 256, 512, 1024). Initial macro parameters are constant: the mass of the system equals 1 kg, the mass of each MP equals to $1/N$, the kinetic energy of the system's center of mass E_S equals 150 J, the system's velocity is directed along the coordinate axis X.

The potential barrier is located in the YZ plane and has a width along the X axis equal to 0.2 m, the barrier's height equals 130 J, the system's internal energy equals 100 J, links rigidity coefficient U_0 equals 300000 N/m. Initial micro parameters, such that coordinates and velocities of the MPs, are set randomly. Each dot in the Figure 5 corresponds to the ratio of change in the system's internal energy to its initial kinetic energy ($\Delta E^{ins} / E_0^{ins}$).

The figure shows that if the number of MPs is greater than 64, then the change in the internal energy can be positive only. This means that for the given parameters of the problem and $N \geq 64$, the system's dynamics is irreversible. This conclusion is made based on the fact that the impossibility of transformation of the system's internal energy into its kinetic energy can be considered as the test for irreversibility. Let us name this number as the first critical number ($N1$). It is obvious that $N1$ depends on the parameters of the problem, for example, on the barrier's width.

AREA OF APPLICABILITY OF D-ENTROPY

In accordance with the law of conservation of momentum, the internal energy of a system cannot be transformed into its kinetic energy, since it is not possible to change the system's momentum. This means that the system is irreversible.

The concept of D-entropy was introduced into the mechanics because of this irreversible energy transformation for a system in a nonhomogeneous external field. D-entropy equals the ratio of the increment of the system's internal energy to its initial value, as well as the entropy of Clausius. Consider a non-equilibrium system that can be represented by a set of SPs in the

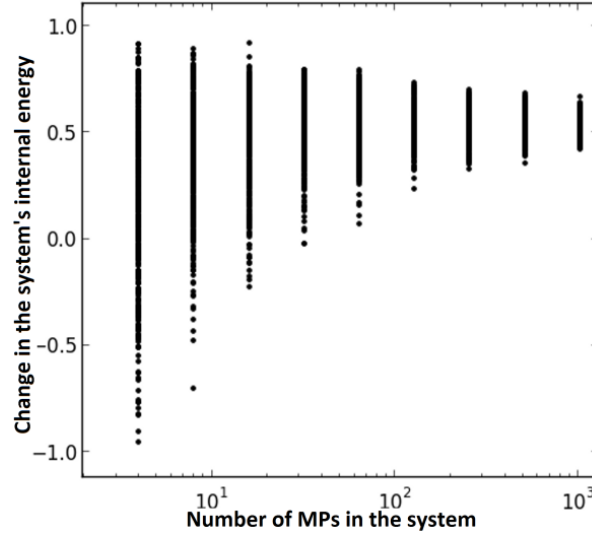


Figure 5. Fluctuations of the system's internal energy subject to the number of MPs.

approximation of local thermodynamic equilibrium; the increment of the D-entropy of this system is proportional to the energy of the relative motion of SPs, which is transforming into their internal energy. In this case, the change in the D-entropy is given by Somsikov (2014a; b):

$$\Delta S^d = \sum_{L=1}^R \{ N_L \sum_{k=1}^{N_L} [\int \sum_s F_{ks}^L v_k dt] / E_L \} \quad (10)$$

where E_L is the internal energy of L^{th} SP; N_L is the number of MPs inside the L^{th} SP; $L=1,2,3,\dots,R$ - number of SPs; S - external MPs interacting with k^{th} MP in the L^{th} SP; F_{ks}^L - the force acting on k^{th} MP of one SP by S^{th} MP of another SP, and v_k - velocity of k^{th} MP.

Equation (10) is obtained based on the equation of motion of a SP, and determines the increment of the SP's internal energy comparing to its initial value. It is valid if the SP is in equilibrium along its path.

In our case $L=1$, so the Equation (10) is determined by a simple formula: $\Delta S^d = \Delta E^{ins} / E_0^{ins}$. This formula can be verified by numerical calculations of ΔE^{ins} for a system passing the potential barrier.

Figure 6 shows average values of change in the system's internal energy ΔE^{ins} over its initial kinetic energy (100 J), as well as confidence intervals for these values. Each confidence interval corresponds to the confidence level of 0.99 (400 experiments) and is calculated as standard deviation of the value multiplied by Student coefficient of 2.6. The values on Figure 6 are in fact the changes in D-entropy ΔS^d up to a constant factor. The calculations show that the value will be positive at $N \geq 8$ with the probability of 0.99; for smaller number of the MPs the value can be negative. As the

number of MPs goes up, the fluctuation tends to zero, and even when $N \geq 10^3$, it becomes approximately equal to 0.1 of the absolute value of ΔS^d .

A further increase in the number of MPs does not change the increment of the internal energy, that is ΔE^{ins} reaches its limit at $N \approx 10^3$. If $N \geq 10^3$, then: $\Delta S^d = \Delta E^{ins} / E_0^{ins} \sim 0.55$. Since a further increase in the number of MPs does not affect the change in the thermodynamic parameters of the system, then $N = 10^3$ can be named as the second critical number (N_2). This number determines the transition to the thermodynamic description for the problem.

CHANGE OF THE ENERGY OF THE SYSTEM PASSING THE BARRIER

Let us compare fluctuations of the system's internal energy depending on the number of MPs and their distribution function, with the law of statistical fluctuations of its mean square value. This comparison is a convincing proof of the possibility of justification of statistical laws based on the laws of mechanics. Let us recall the way it is usually proved that the relative fluctuation of any additive parameter of a system is inversely proportional to \sqrt{N} , where N is the number of elements in the system, on the basis of statistical laws (Landau, 1976).

The internal energy of the system (E^{ins}) is an additive value. If the system is divided into N subsystems, then the average value of its internal energy is equal to the sum of the average values of the internal energies of all subsystems, that is, $|E^{ins}| = \sum_{i=1}^N |E_i|$. Let us start from

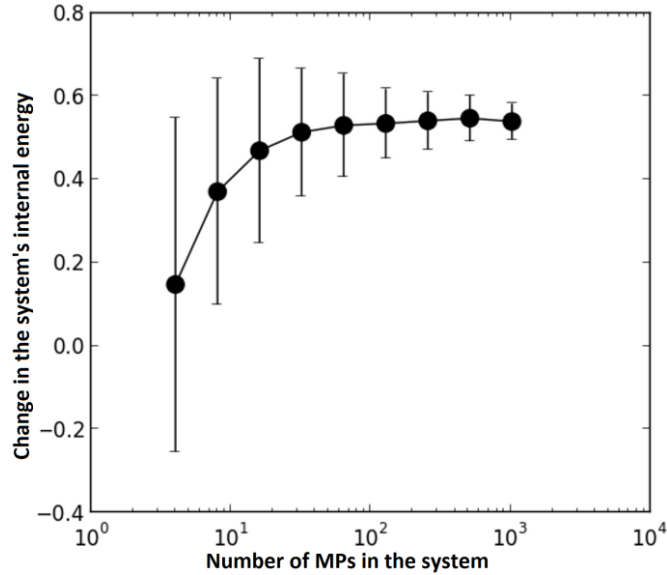


Figure 6. Change in the system's internal energy subject to the number of MPs.

the fact that the internal energy increases in proportion to the number of MPs. Then the mean square value of the fluctuations of the internal energy equals $|(\Delta E)^2| = |(\sum_{i=1}^N \Delta E_i)^2|$. If the fluctuations in the subsystems are independent, then $|(\Delta E)^2| = \sum_{i=1}^N |(\Delta E_i)^2|$. Hence the well-known law is obtained: $|(\Delta E)^2|^{1/2} \sim 1/N^{1/2}$.

Thus, if the calculated value of the relative fluctuations of E^{int} varies inversely to \sqrt{N} , then this fact will serve as a proof of both the law of the fluctuations, and the possibility of the justification of this law by the laws of classical mechanics.

Figure 7 shows that dots, corresponding to the fluctuations of the internal energy, fit the curve corresponding to the statistical law of decrease of fluctuations in the system with the increase in the number of its elements (Landau, 1976).

This means, firstly, that the numerical simulations of the system passing through the barrier are correct, secondly, that the dualism of energy is reflected in the statistical laws, and thirdly, that the laws of classical mechanics are suitable not only for justification of the statistical laws, but also for determining the scope of their application depending on the parameters of the system.

The slight difference between the calculated fluctuations of ΔE^{ins} and the approximating line can be explained by the fact that the increase in the number of MPs results in a change of other parameters of the system that affect the value of ΔE^{ins} (for example, size of the system). Another reason for a certain deviation from the statistical law may be the fact that for a given

number of MPs the system cannot be strictly considered as an equilibrium one. In general, the study of these deviations may be useful to identify the areas of applicability of statistical laws in the specific problems of dynamics.

CHANGE IN THE INTERNAL ENERGY SUBJECT TO THE WIDTH OF THE BARRIER

According to the equation of motion of the system, the change in the system's internal energy ΔE^{ins} nonlinearly depends on the micro and macro variables and is different from zero only when the scale of nonhomogeneity of the external field is about the scale of the system. The value of ΔE^{ins} should increase as the difference between the forces acting on different areas of the system goes up (Landau, 1976; Rumer and Rivkin, 1977). This conclusion is checked by calculating the dependence of ΔE^{ins} on the barrier's width. Figure 8 shows the results of these calculations.

The ordinate axis is the ratio of change in the internal energy to the initial energy of motion of the system's center of mass. The solid vertical line represents the standard deviation of coordinates of MPs (a measure of the system's size). The dotted line represents the maximum size of the system (the maximum distance between the MPs during the numerical experiment).

According to Figure 8, there is a decrease in the efficiency of transformation of the system's kinetic energy into its internal energy, with the increase in the barrier's width, that is, as gradient of the external field goes down,

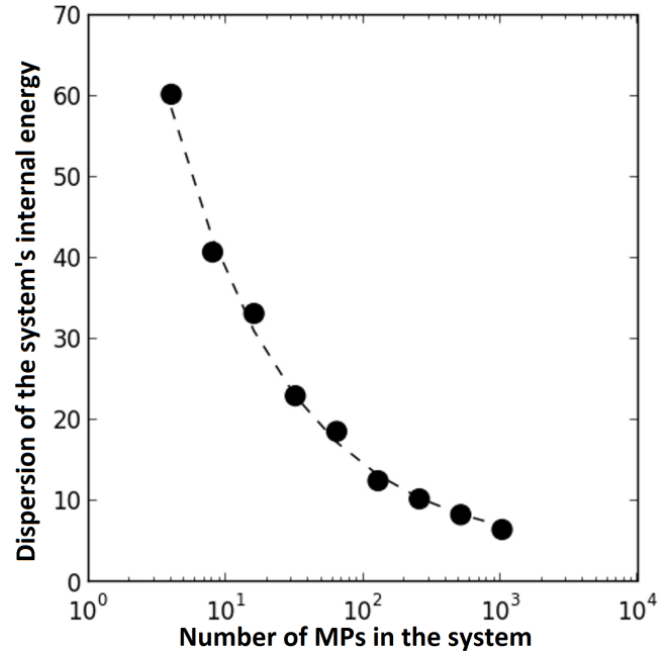


Figure 7. Dots: max amplitude of fluctuation of ΔE^{ins} subject to number of MPs. Approximating line is given by $= p + r/\sqrt{N}$, where $p=3.5$, $r=110$.

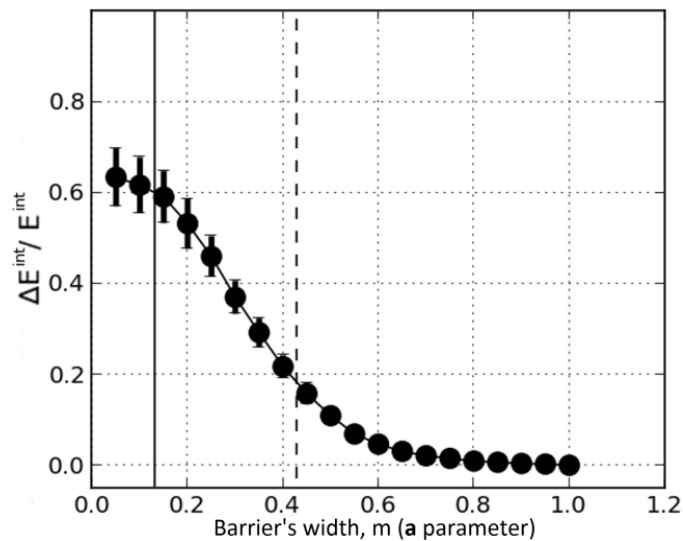


Figure 8. Change in the internal energy subject to the barrier's width, a .

then the change in the internal energy tends to zero. The law of diminishing is close to power-law dependence. The dependence of the internal energy on the gradient of the external forces follows from the Equation (8), if we expand the external force in the small parameter (Somsikov, 2014b).

All of the results of numerical simulations are obtained here only because the calculations were based on the concept of deterministic mechanism of irreversibility. Previously proposed D-entropy is calculated in accordance with this mechanism based on the rigorous equations of motion of systems (Somsikov, 2014b). The

D-entropy can be determined only if one uses the principle of symmetry dualism and consequent principle of energy dualism. The sum of the system's kinetic energy and its internal energy was constant during the calculations; this verified compliance with the law of conservation of energy.

CONCLUSION

Numerical simulations of dynamic parameters of motion of an equilibrium system of potentially interacting MPs in a nonhomogenous external field revealed the following patterns. A critical number of MPs is determined, such that the system's internal energy cannot go down for any given initial state of the system. In our case, this number, $N1 \sim 10^2$. That is, when the number of SPs is greater than $N1$, then the system's dynamics becomes irreversible. This number specifies the minimum number of MPs in the system which is needed in order to apply a concept of D-entropy S^d .

Let us note that the value of $N > 10^2$ is obtained for a specific model. In general, the value of $N1$ should differ for a system with different parameters. But the main thing is not the exact value of $N1$, but the fact that it can be determined using the laws of Newton. This fact is a strong argument for an idea that the laws of thermodynamics can be obtained within the frameworks of classical mechanics without use of statistical hypotheses. Moreover, it supports the idea that the statistical laws themselves can be obtained using the laws of classical mechanics

The second critical value ($N2$) has been found. In our case $N2 = 10^3$. The increase in the system's internal energy ΔE^{ins} stabilizes if the number of its elements is greater than 10^3 . In our case asymptotic value of $\Delta E^{ins} \sim 0.55$. The value of $N2$ determines the transition to the thermodynamic description for the system.

It is shown that the relative fluctuations of E^{ins} goes down when the number of MPs goes up. The rate of this decrease is inversely proportional to \sqrt{N} . This relation for a system is obtained on the basis of the equations of dynamics and this fact is an argument in favor of the idea that the statistical laws should be justifiable under the laws of classical mechanics. Since the law of fluctuations is the basis of statistical physics (Landau, 1976), this fact indicates the possibility of justification of statistical laws based on the laws of physics.

The efficiency of transformation of the system's kinetic energy into its internal energy goes down while the gradient of the external forces decrease. This dependence shows that the change in the internal energy is due to non-potential forces which themselves are proportional to the gradients of the external forces.

The numerical simulations carried out on the basis of the equation of SP's motion, allowed defining numerical

criteria for the transition from a dynamic description to the thermodynamic model depending on the number of MPs. This opens the way for the justification of the laws of thermodynamics under the laws of classical mechanics.

Overall, the results confirm the need to describe the dynamics of systems in accordance with the principle of dualism of symmetry and use of the equation of SP's motion. Given that the real bodies are structured, it is dualism that allows identifying and study the connection between the laws of classical mechanics and the empirical laws of thermodynamics and statistical physics.

Conflict of Interest

The authors have not declared any conflict of interest.

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Full Length Research Paper

Financial planning for the preventive maintenance of the power distribution systems' critical components using the reliability-centered approach

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Among different maintenance strategies that exist for power distribution systems, the Reliability-Centered Maintenance (RCM) strategy attempts to introduce a structured framework for planning maintenance programs by relying on network reliability studies and cost/benefit considerations. For the implementation of the RCM strategy, the electricity distribution companies try to optimally utilize the existing financial resources in order to reduce the maintenance costs and improve the reliability of the network. The aim of this paper is to present a practical method for devising an appropriate maintenance strategy for network elements and for preventive maintenance budget planning, with the goal of improving the system reliability and reducing the maintenance costs. In the proposed method, the critical outage causes of the distribution system are determined on the basis of cost and reliability criteria, by the Technique for order preference by similarity to ideal solution (TOPSIS) method. Then, the optimum preventive maintenance budget is calculated by obtaining the cost functions of the critical elements and optimizing the overall cost function. In this investigation, the medium voltage distribution network of the "Haft Tir" district in Tehran has been chosen for the implementation of the proposed RCM strategy.

Key words: Reliability-centered maintenance (RCM), preventive maintenance (PM), technique for order preference by similarity to ideal solution (TOPSIS), power distribution system.

INTRODUCTION

One of the most important goals of power distribution companies is to provide uninterrupted and quality service to their customers (Brown, 2002). In this regard, the electricity distribution companies try to select an optimum maintenance strategy in order to reduce the failure rate of network equipment and increase the reliability of the system. This objective was not accomplished as desired in traditional maintenance methods in which the repair of

network components was performed at specific time intervals. The huge maintenance expenditures and the inefficiency of these methods in reducing the outages in the system made it necessary to develop a more effective and comprehensive maintenance strategy; a strategy based on the ability to monitor network reliability and to consider the interrelationship between reliability and maintenance costs. These necessities gradually caused

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the maintenance strategies to be inclined towards the reliability-centered strategies and away from the time-based strategies. The Reliability-Centered Maintenance (RCM) strategy attempts to present an organized framework for the improvement of network reliability and the reduction of maintenance expenses by relying on cost/benefit studies and the reliability analysis of networks (Schneider et al., 2006; Ghadimi, 2012; Ahadi et al., 2014a). In the RCM strategy, the corrective and preventive maintenance strategies are subjected to cost/benefit analysis, and the optimum strategy is selected (Ahadi et al., 2014b).

The preventive maintenance strategy has many complexities relative to the corrective maintenance strategy. Knowing the priorities of elements for preventive measures and determining the proper time intervals between these activities are some of the challenges faced by the preventive maintenance engineers of power distribution companies (Ahadi et al., 2014b; Hagh et al., 2011). However, one of the most important problems that need to be addressed in preventive maintenance planning is the manner of allocating the preventive maintenance budget to the weak points of the network. The assessment of a preventive maintenance budget has always been difficult because of certain factors such as the outages due to environmental and human causes and the unknown nature of some causes of outages, especially the transient ones.

The maintenance budget limitation of the distribution companies, on one hand, and the complexity of assessing the PM budget, on the other hand, have made it necessary to conduct fundamental studies on the subject of maintenance budget planning. This issue is so important that in some cases, due to an incorrect assessment of the maintenance budget, network reliability may not improve much, even though vast maintenance resources are spent.

The establishments of an appropriate relationship between the preventive maintenance of an electricity distribution system and its reliability and the achievement of a RCM strategy have always been of interest to the researchers (Bertling et al., 2005; Ghadimi, 2012). However, due to the lack of proper network information, so far, RCM strategy has not been implemented adequately (Bertling et al., 2005). In Ahadi et al. (2014b) and Bertling et al. (2005), the implementation of the RCM strategy in the power distribution system of Stockholm, Sweden, has been discussed. In this method, optimal scenarios for dealing with the outage causes in the system are selected based on network reliability and cost-benefit analyses. The implementation of RCM in the distribution system has also been studied in Schneider et al. (2006) and Ghadimi (2012). In this method, by determining the failure rate of the critical failure modes, the strategies for dealing with these failure causes undergo cost-benefit analysis.

Also in some studies, the manner of implementing an

optimal preventive maintenance strategy in electricity distribution systems for the purpose of network reliability improvement has been investigated. In Lie and Chun (1986) an algorithm is introduced for determining what type of preventive maintenance to consider for the components of a distribution network and when to apply this particular PM strategy. Sobhani and Ghadimi (2013) and Wallnerströmand et al. (2013) and deal with preventive maintenance planning based on risk assessment. As the distribution system components continue to operate, their failure probability increases and therefore the resulting risk goes up. An optimal maintenance model reduces the risk of component failure. In Hagh and Ghadimi (2014), the instant causes of failure in Tehran's electricity distribution system are classified and ranked, and the more important factors are selected for the implementation of preventive maintenance activities. In this reference, after finding the most prevalent causes of instantaneous failures, the variables with higher priorities are selected. In Mohammadi and Ghadimi (2014), the minimization of power outage cost and maintenance cost constitutes the objective function. Ultimately, the results of applying this method in the Birka system of Sweden are evaluated. In Teera-achariyakul et al. (2010), the duration of consumer power outage is minimized through the optimal allocation of a maintenance budget. In Maleh et al. (2013), the allocation of a maintenance budget for distribution feeders is investigated. In the proposed model, the failure rates of feeders are modeled as functions of PM budget, and the cost of PM is minimized by considering a suitable maintenance budget. Park et al. (2000), Canfield (1986) and Mohammadi and Ghadimi (2013) focus on the minimization of preventive maintenance cost. This cost includes the cost of power outage, cost of maintenance, cost of replacement and the annual cost of repairs. In Sittithumwat et al. (2004), the reliability indexes are expressed as probabilities, and by determining the maintenance level, it is attempted to reduce the system average interruption frequency index (SAIFI).

In large electricity distribution networks with numerous causes of power failure, the implementation of the RCM strategy based on determining the proper intervals between preventive activities and optimum maintenance scenarios faces many difficulties; because the assessment of different maintenance scenarios for network components and the reduction of component failures in these scenarios, and in brief, the cost/benefit analysis of maintenance scenarios is impossible without having a sufficient knowledge of the causes of network elements failures. Also, in planning for a maintenance budget, it is necessary to appropriately select a maintenance strategy for network components based on the costs incurred by component failures and the role of components in network reliability. Therefore, if an appropriate maintenance strategy is selected for the network components and the PM budget is optimally

spent for the improvement of network reliability and the reduction of maintenance costs, a favorable RCM strategy can be achieved. This paper tries to present a practical method for selecting an optimal maintenance strategy and for the financial planning of a preventive maintenance budget for power distribution networks with the goals of improving network reliability and reducing maintenance costs. In this approach, after prioritizing the outage causes and recognizing the critical outage causes by the TOPSIS method, the maintenance cost functions of the outage causes are obtained with respect to the PM budget and network information, and then by minimizing the total maintenance cost, the optimum PM budget is calculated. To implement the proposed methods, the medium-voltage distribution network of the “Haft Tir” district in the city of Tehran has been selected as the sample network. The reliability information of this study is based on the outage information of the years 2005-2012 that has been extracted from the events logging software of the Greater Tehran Electricity Distribution Company (GTEDC) known as the ENOX Database.

Under proposed method of this paper, the process of PM budget allocation by the proposed method is described. This is followed by results of budget planning by this method for the sample distribution network. Effect of the proposed method on the improvement of network reliability and the reduction of maintenance cost in the studied network is further investigated, and the conclusion is presented.

PROPOSED METHODS

For proper maintenance budget planning, first, it is necessary to devise a suitable maintenance strategy for the outage causes. An appropriate maintenance strategy is selected based on the role of different elements in network reliability and the costs imposed on the system.

After choosing an appropriate maintenance strategy and a PM strategy for the critical outage causes, it is necessary to establish the right relationship between the PM budget and network reliability and to determine the cost of maintaining network components, which mostly includes the cost of repairs, cost of energy not supply, cost of human resources and the cost of preventive maintenance. After obtaining the maintenance cost functions, the optimal PM budget of critical outage causes is calculated by optimizing the overall cost function. If the allocated budget does not lead to the reduction of maintenance cost and the improvement of network reliability as desired, the total PM budget will have to be increased. Figure 1 shows the flowchart of PM budget allocation procedure.

As is shown in the flowchart of Figure 1, the PM budget planning process comprises three major steps:

- 1) Prioritizing the outage causes and choosing the critical outage causes
- 2) Estimating the maintenance cost functions of the critical outage causes
- 3) Calculating the optimum budget of the critical outage causes

Prioritizing the outage causes and choosing the critical outage causes

Certainly, choosing an appropriate preventive maintenance strategy

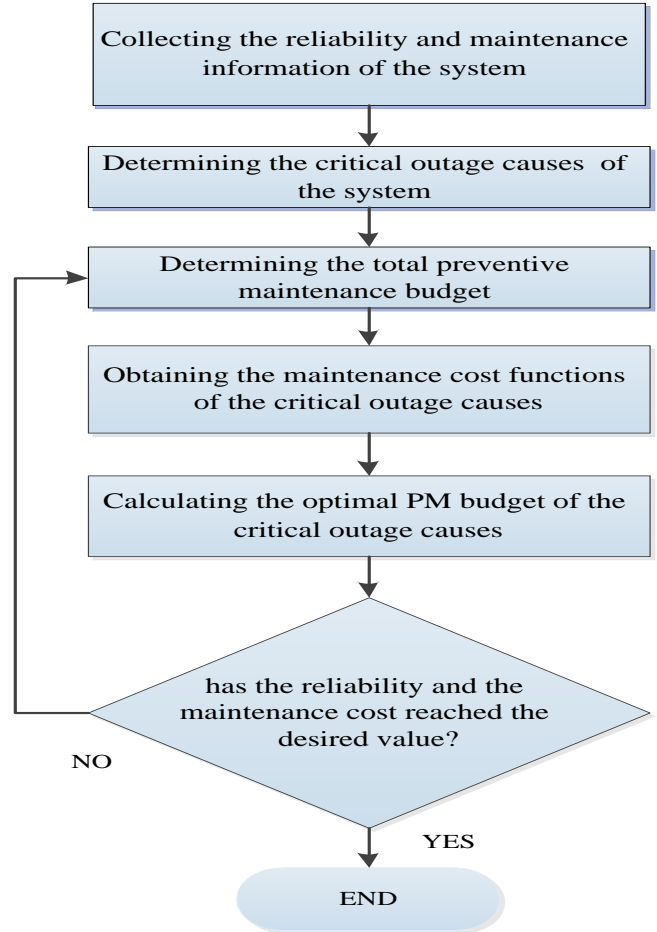


Figure 1. Flowchart for the allocation of preventive maintenance budget.

for sensitive and effective equipment in the distribution network rather than spending huge sums of money on the maintenance of all network elements, regardless of their role and importance in the system, will lead to more economical as well as optimal decisions. Those outage causes that have a higher influence on network reliability and the maintenance cost imposed on the network are called the “critical outage causes”.

Since numerous factors such as the replacement cost of equipment, number of equipment, and the functions of elements in achieving network reliability must be considered in the selection of the critical outage causes, the multi-criteria decision-making methods (MCDMs) can be employed to prioritize the outage causes and to choose the right maintenance policy. In the proposed method, to prioritize the outage causes, these factors are compared with one another by the TOPSIS method by considering the indexes associated with network reliability, repair cost of components and the number of components. Weights are assigned to the main decision-making criteria based on the priorities of the electricity distribution companies and the opinions of these companies’ maintenance engineers. After computing the priorities of the outage causes by the TOPSIS approach, the outage causes with higher priorities are selected for preventive maintenance strategy and those with lower priorities are selected for corrective maintenance strategy. Figure 2 shows the process of prioritizing the outage causes and selecting a maintenance strategy for them by the TOPSIS method.

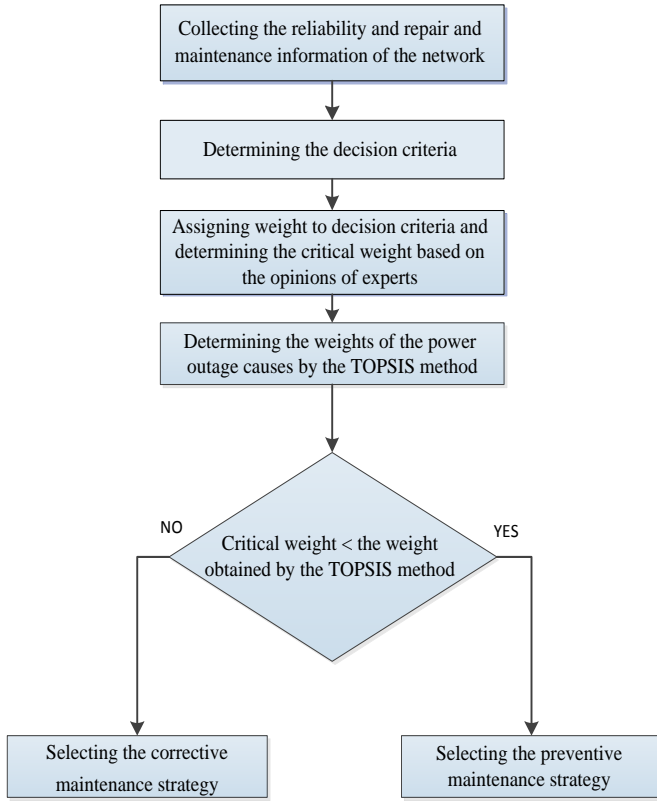


Figure 2. Flowchart for selecting a maintenance strategy for the outage causes by the TOPSIS method.

In the MCDMs of TOPSIS, which was presented in 1981 by Hwang and Yoon, the best solution is the one which is the closest to the positive-ideal solution and, at the same time, the farthest away from the negative-ideal solution (Ghadimi et al., 2014). The ideal solution represents a hypothetical choice which is the most favorable standardized weighted choice from each criterion among the considered choices; and the negative-ideal solution comprises the worst standardized weighted choice among the various choices.

The TOPSIS method evaluates a decision matrix that has M choices and N indices. A_i indicates the i th choice, X_j indicates the j th index and X_{ij} is the numerical value obtained from i th choice and j th index. In the following, the step-by-step prioritization of the choices by the TOPSIS method is described according to Ghadimi et al. (2014).

Step 1: Normalization of the decision matrix

This process tries to non-dimensionalize the existing quantities in the decision matrix. To do this, each value is divided by the magnitude of the vector corresponding to the same index. Every entry of the normalized decision matrix is obtained from Equation (1).

$$r_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^m X_{ij}^2}} \tag{1}$$

Step 2: Assigning weight to the normalized matrix

The decision matrix is, in fact, parametric and it needs to become quantified. To this end, the decision-maker assigns a weight to each index and the sum of weights (W) is multiplied by the normalized matrix R.

$$W = (W_1, \dots, W_n) \tag{2}$$

$$\sum_{j=1}^n W_j = 1 \tag{3}$$

Step 3: Determining the ideal and negative-ideal solutions

The two virtual choices of A^* and A^- are defined as follows:

$$A^* = \{(\max_i V_{ij} | j \in J), (\min_i V_{ij} | j \in J')\} | i = 1, 2, \dots, m \tag{4}$$

$$= \{V_1^*, \dots, V_n^*\}$$

$$A^- = \{(\min_i V_{ij} | j \in J), (\max_i V_{ij} | j \in J')\} | i = 1, 2, \dots, m \tag{5}$$

$$= \{V_1^-, \dots, V_n^-\}$$

A^* is the positive-ideal and A^- is the negative-ideal solutions, J is the benefit criterion column and J' indicates the cost criterion column.

Step 4: Obtaining the separation measures

The separation of choice i from the positive- and negative-ideal solutions is estimated.

$$S_i^* = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^*)^2} \quad i = 1, 2, \dots, m \tag{6}$$

$$S_i^- = \sqrt{\sum_{j=1}^n (V_{ij} - V_j^-)^2} \quad i = 1, 2, \dots, m \tag{7}$$

Step 5: Calculating the relative closeness to the ideal solution

This criterion is obtained from Equation (8).

$$C_i^* = \frac{S_i^-}{S_i^* + S_i^-} \quad 0 < C_i^* < 1 \tag{8}$$

Obviously, the less the separation of choice is from the ideal solution, the closer the relative closeness will be to 1.0.

Step 6: Ranking the choices

Finally, the choices are ranked in a descending order.

Table 1. Weights of selected criteria for the prioritization of the studied system's.

Decision criteria	Weights of the decision criteria
Number of outages	0.265
Duration of outages	0.24
Energy Not Supply	0.24
Equipment Replacement Cost	0.125
Number of Existing Elements	0.13

Estimating the maintenance cost functions of critical outage causes

To obtain the maintenance functions of the outage causes, it is necessary to determine their failure rate functions with respect to the PM budget. It is obvious that the bigger the PM budget is, the more the failure rate of components will be reduced. The function of failure rate versus PM budget is expressed as a function with exponential distribution according to Equation (9) (Schneider et al., 2006; Ghadimi, 2012; Maleh et al., 2013; Sarchiz et al., 2009)

$$\lambda(PM_i) = A_i + B_i e^{-C_i PM_i} \tag{9}$$

After determining the failure rate functions of the critical outage causes, the functions of repair cost, energy not supply cost and human resources cost are obtained by Equation (10) through Equation (12).

$$TC_i^{re} = \lambda(PM_i) \cdot C_i^{re} \tag{10}$$

$$TC_i^{ENS} = \lambda(PM_i) \cdot ENS_i^{avg} \cdot C_{ENS} \tag{11}$$

$$TC_i^{hr} = \lambda(PM_i) \cdot hr_i^{avg} \cdot C_{hr} \tag{12}$$

Calculating the optimum PM budget of the critical outage causes

The total maintenance cost is obtained by summing the repair cost, energy not supply cost, human resources cost and the preventive maintenance cost. By considering the total PM budget and the changes of the elements' failure rates, the optimum preventive maintenance budget is obtained by minimizing the total maintenance cost of the critical outage causes. The objective function and the governing constraints of the problem are according to Equation (13) through Equation (15).

$$Minimize : TCCM = \sum_{i=1}^n TC_i^{re} + TC_i^{ENS} + TC_i^{hr} \tag{13}$$

$$\sum_{i=1}^n PM_i = TCPM \tag{14}$$

$$\lambda_i^{min} \leq \lambda_i \leq \lambda_i^{max} \tag{15}$$

CASE STUDY RESULTS

To implement the proposed methods, the medium-

voltage distribution network of the "Haft Tir" district in the city of Tehran has been selected as the sample system. The "Haft Tir" electricity distribution district, with an area encompassing about 140 km², is one of the largest regions in Tehran municipality. This investigation has been based on the outage information of the mentioned network for the years 2005-2012, which has been extracted from the incidents logging software (known as ENOX) of the Greater Tehran Electricity Distribution Company (GTEDC). The goal of this investigation is to plan the PM budget of the year 2013 for this system based on the system reliability and cost information of this system.

After collecting the reliability and maintenance cost information of the sample system, the process of PM budget allocation, according to the procedure described in proposed method, includes the steps of prioritizing the outage causes and determining a suitable maintenance strategy, obtaining the maintenance cost functions and calculating the optimal PM budget for the critical outage causes.

Prioritizing the outage causes and choosing the critical outage causes by the TOPSIS method

Identifying the critical outage causes is very important for the purpose of choosing an appropriate maintenance strategy. For certain outage causes such as operator error, equipment theft, disastrous climatic conditions and unanticipated events, proper preventive measures cannot be considered. After collecting the outage information of the sample system, separated by the cause of outage, the selected outage causes are classified into 13 groups for the selection of preventive and corrective maintenance policies. Table 2 shows the unplanned outage causes of the studied system.

The main selected criteria for the prioritization of outage causes include the number of outages, duration of outages, energy not supply, equipment replacement cost and the number of existing elements in the system. The weights of the decision criteria are determined based on the priorities of the Tehran power distribution company and the knowledge of the maintenance engineers of this company, according to Table 1.

Based on the information of the studied system, the columns and rows of the decision matrix are established

Table 2. Determining the priorities of the studied system's outage causes on the basis of decision criteria by the TOPSIS method.

Group	Failure cause	TOPSIS weight
1	Failure of capacitor bank	0.1174
2	Fault of the medium voltage cable	0.397
3	Failure of structure	0.298
4	Failure of transformer	0.575
5	Failure of lightning arrester	0.148
6	Failure of Insulator	0.125
7	Failure of disconnecter switch	0.274
8	Failure of circuit breaker	0.437
9	Failure of cutout switches	0.134
10	Failure of cable terminations	0.204
11	Failure of recloser	0.1748
12	Fault in the main switch or the low voltage board	0.0439
13	Tree contact	0.259

Table 3. Critical outage causes of the studied system.

Group	Outage cause
A	Failure of transformer
B	Failure of cable terminations
C	Failure of circuit breaker
D	Failure of structure
E	Fault of the medium voltage cable
F	Failure of disconnecter switch
G	Tree contact

based on the decision criteria and the information of outage causes, respectively; and the priorities of the outage causes are calculated by the TOPSIS method. The priorities of the outage causes of the studied system obtained by the TOPSIS method have been listed in Table 2. After determining the outage causes and considering a critical weight of 0.15 based on the opinions of the Greater Tehran Electricity Distribution Company's Engineers, seven groups of outage causes with priorities larger than the critical weight are selected for preventive maintenance strategy and the remaining outage causes are chosen for corrective maintenance strategy. Table 3 shows the outage causes of the studied system selected for PM budget planning.

Determining the maintenance cost functions and calculating the PM budget of critical outage causes

After selecting the critical outage causes of the system under study, based on the information of this system, the failure rate functions of the critical outage causes are determined as a function of PM budget, according to

Equation (9). Table 4 shows the coefficients of the failure rate functions of the studied systems' critical outage causes.

The maintenance cost is obtained by adding up the repair cost, energy not supply cost, human resources cost and the preventive maintenance cost. The preventive maintenance budget of the critical outage causes is calculated according to Equation (13) through Equation (15) by optimizing the maintenance cost, considering the limitation of the total PM budget and taking into account the failure rate changes of the critical outage causes. Table 5 shows the information related to the studied system for determining the optimum PM budget, which includes the coefficients of the failure rate functions, average repair cost of elements, minimum and maximum failure rates of critical elements and the average amount of energy not supply and human resources for each time an element failures. The total PM budget of the investigated system for the year 2013 is 543,472 dollars, based on the planned budget of the Greater Tehran Electricity Distribution Company. Also, the cost of energy not supplied (C_{ENS}) has been considered as 8 dollars per kWh and the human resources

Table 4. coefficients of the failure rate functions of the sample systems's critical outage causes.

Group	A_λ (int/year)	B_λ (int/year)	$C_\lambda * 10^5$
A	39	129.5	3.4
B	59	123.9	7.78
C	41	162.2	1.81
D	18	66.1	5.9
E	41	194.3	1.79
F	31	88.1	5.94
G	26	124.45	1.55

Table 5. Determining the priorities of the studied system's outage causes on the basis of decision criteria by the TOPSIS method.

Group	A_λ (Int/year)	B_λ (Int/year)	$C_\lambda * 10^5$ (Int/year)	C^{rp} (\$)	ENS_i^{avg} (KWh)	λ_{min} (Int/year)	λ_{max} (Int/year)	hr_i^{avg} (individual *hour)
A	39	129.5	3.4	285	1327	46	109	18
B	59	123.9	7.78	58	201	59	106	11
C	41	162.2	1.81	181	1021	58	156	14
D	18	66.1	5.9	170	936	18	28	21
E	41	194.3	1.79	123	1421	58	160	12
F	31	88.1	5.94	110	353	31	57	16
G	26	124.45	1.55	62	926	55	116	12

cost (C_{hr}) has been set as 11 dollars per individual per hour. The GAMS software and the nonlinear programming method have been employed to analyze the existing problem. Figure 3 shows the PM budget of the investigated system's critical outage causes estimated by the proposed method.

DISCUSSION

Here, the proposed method were implemented in the studied system. In addition to these method, it can be assumed that the share of each group of critical outage causes from the total PM budget of 2013 is similar to that of 2012 budget, and that no change is made in the budget planning method of 2013 relative to 2012. Thus, the PM budget of 2013 for the outage causes can be computed based on the 2012 budget for these causes. Figure 4 shows the PM budget planning for the studied system's outage causes by the proposed method along with the PM budget planning based on the 2012 budgeting procedure. In order to estimate the improvement of system reliability due to PM budget planning through the two said methods, the index of system reliability improvement is defined by Equation (16) (Ghadimi, 2012).

$$RII = \alpha \frac{\lambda - \lambda_{base}}{\lambda_{base}} + \beta \frac{U - U_{base}}{U_{base}} + \gamma \frac{ENS - ENS_{base}}{ENS_{base}} \tag{16}$$

Weighting coefficients α, β, γ are determined based on the priorities of the electricity distribution companies. To calculate the system reliability indexes of the two budget planning methods in the system under investigation, the functions of failure rate, outage duration and energy not supply versus PM budget are considered as exponential distribution functions according to Equation (17) through Equation (19).

$$\lambda(PM_i) = A_i^\lambda + B_i^\lambda e^{-C_i^\lambda PM_i} \tag{17}$$

$$U(PM_i) = A_i^U + B_i^U e^{-C_i^U PM_i} \tag{18}$$

$$ENS(PM_i) = A_i^{ENS} + B_i^{ENS} e^{-C_i^{ENS} PM_i} \tag{19}$$

The coefficients of functions (17) through (19) can be calculated with regards to the information of the studied system. Table 6 show the coefficients of failure rate, outage duration and energy not supply functions of the investigated network's critical outage causes. Thus, based on the obtained functions and the amount of PM budget,

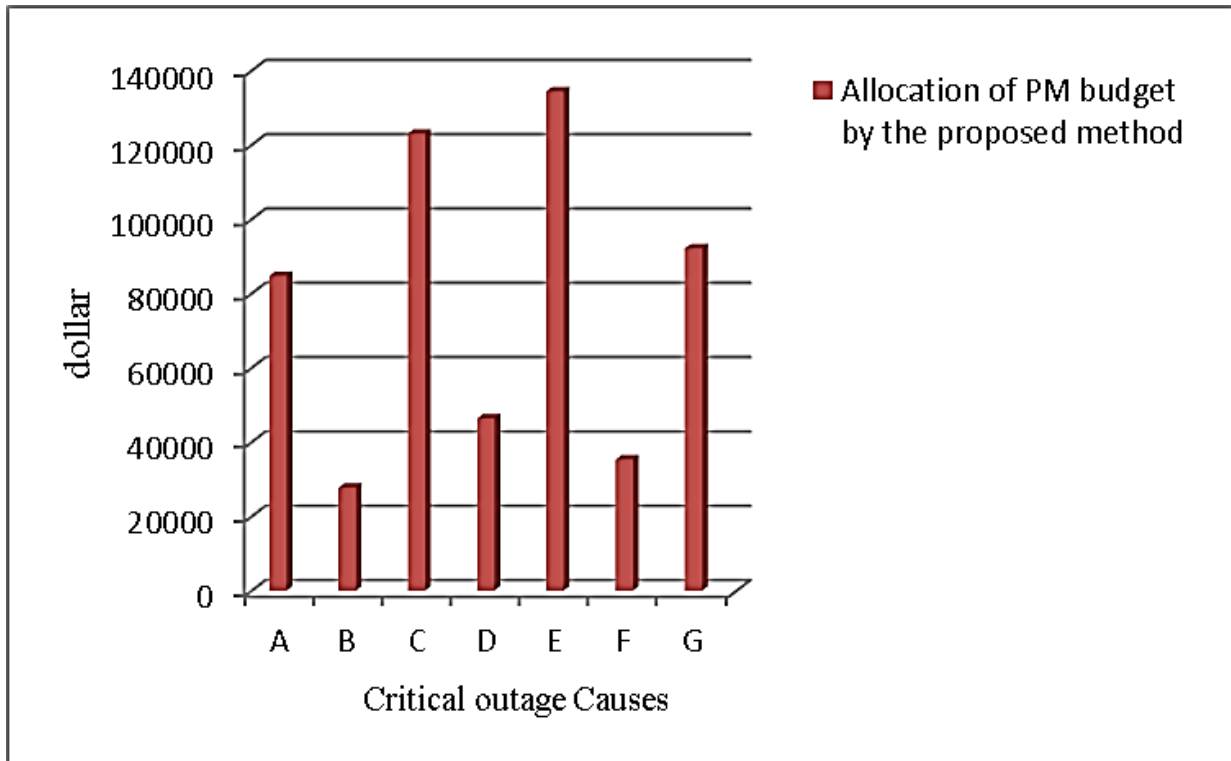


Figure 3. Allocation of PM budget to the studied system's critical outage causes by the cost optimization method.

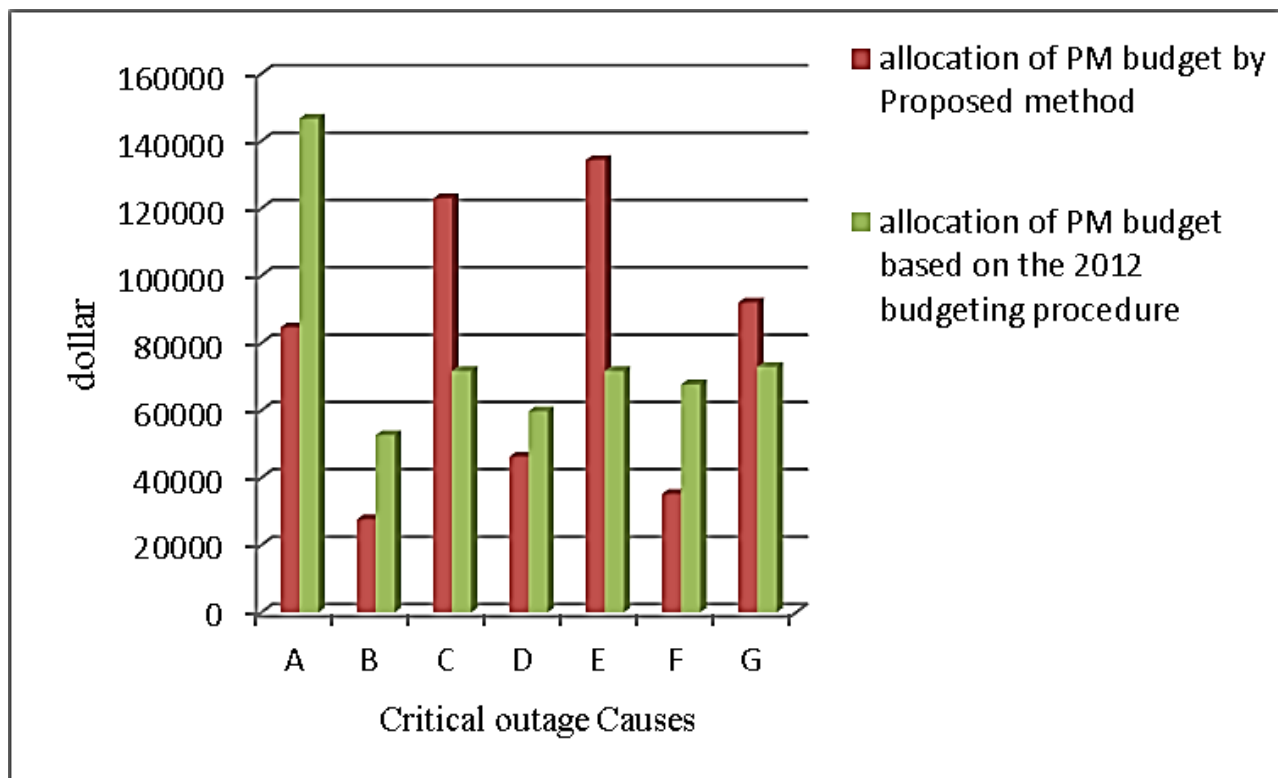


Figure 4. PM budgets of the studied network's critical outage causes obtained by the proposed method and by the budgeting procedure of the year 2012.

Table 6. Coefficients of failure rate, outage duration and energy not supply functions of the studied system’s critical outage causes.

Group	A^λ (Int/year)	B^λ (Int/year)	$C^\lambda * 10^5$	A^U (Minute)	B^U (Minute)	$C^U * 10^5$	A^{ENS} (MWh)	B^{ENS} (MWh)	$C^{ENS} * 10^5$
A	39	129.5	3.4	1411	14280	0.637	19	114.39	0.691
B	59	123.9	7.78	1100	6234	0.221	6	12.04	0.241
C	41	162.2	1.81	1623	13650	0.690	26	108.37	0.351
D	18	66.1	5.9	1152	11260	0.487	12	62.22	0.256
E	41	194.3	1.79	1920	19680	0.392	41	125.4	0.314
F	31	88.1	5.94	905	6729	0.415	9	12.03	0.451
G	26	124.45	1.55	1423	13140	0.490	19	75.33	0.207

Table 7. Maintenance cost and reliability improvement index of the studied system obtained by proposed method and budget planning based on the year 2012 budget with considering $\alpha = 0.448$, $\beta = 0.338$, $\gamma = 0.214$.

Method	RII	Maintenance cost (dollar)
Proposed method	0.054	3,096,528
budget allocation of the year 2012 method	0.01	3,683,660

the reliability improvement index is determined according to Equation (16). Also, the maintenance costs of the studied system through the two budget planning approaches can be found by Equation (10) through Equation (13). Table 7 presents the indexes of reliability improvement and maintenance cost of the investigated system obtained by the proposed method and by budgeting procedure of the year 2012 with considering $\alpha = 0.448$, $\beta = 0.338$, $\gamma = 0.214$.

As is observed, by considering an identical total PM budget, the degree of network reliability improvement and the maintenance cost are higher in the proposed method compared to those obtained by the budget planning method of 2012. The establishment of an appropriate relationship between preventive maintenance, maintenance cost and network reliability in this method leads to the optimal expenditure of the PM budget for the improvement of network reliability and the reduction of maintenance costs.

Conclusion

Two major objectives are pursued in the implementation of preventive maintenance programs for an electricity distribution system: the improvement of network reliability and the reduction of maintenance costs. In this paper, a method has been presented for selecting the proper strategy for the maintenance of network components and for planning an appropriate preventive maintenance budget, with the goal of improving network reliability and reducing the maintenance cost. In this approach, after

prioritizing the power outage causes and determining the critical power outage factors by the TOPSIS method, the maintenance cost function is obtained, and based on the reliability information of the network, the amount of budget that leads to a minimum maintenance cost is calculated.

The results of implementing this method in the medium voltage distribution network of the “Haft Tir” district in the city of Tehran indicate that by using this method in PM budget planning, network reliability improves and the maintenance cost is lowered. The establishment of an appropriate relationship between preventive maintenance, network reliability and maintenance cost in this method makes it possible to optimally spend the PM budget for the improvement of network reliability and the reduction of maintenance cost. Since the implementation of the RCM strategy based on the cost/benefit studies of different maintenance scenarios for network components runs into many difficulties in electricity distribution networks with numerous power outage causes, by applying this method, a favorable RCM strategy can be implemented.

Conflict of Interest

The authors have not declared any conflict of interest.


NOMENCLATURE; A^* , Positive ideal solution in the TOPSIS method; A^- , negative ideal solution in the TOPSIS method; $A_i^{ENS}, B_i^{ENS}, C_i^{ENS}$, coefficients of energy

not supply functions with respect to the PM budget of the i th component; A_i^U, B_i^U, C_i^U , coefficients of outage duration functions with respect to the PM budget of the i th component; $A_i^\lambda, B_i^\lambda, C_i^\lambda$, coefficients of failure rate functions with respect to the PM budget of the i th component; C_{ENS} , cost of 1.0 kWh of energy not supply (in dollars); C_{hr} , average cost of one hour of human resources (in dollars); C_i^{re} , average repair cost of the i th component forevery failure (in dollars); ENS_i , annual energy not supply of the i th component (in MWh); ENS_i^{av} , average energy not supply in the failure of the i th component (inKwh); hr_i^{av} , average human resources needed in the failure of the i th component (in individual *hour); J , set of profit indexes in the TOPSIS method; J' , set of cost indexes in the TOPSIS method ; PM_i , PM budget of the i th component (in dollars); R_{II} , system reliability improvement index; r_{ij} , element of the i th row and j th column of the decision matrix normalized by the TOPSIS method; S_i^+ , ideal separation in the TOPSIS method; S_i^- , negative ideal separation in the TOPSIS method; TC_i^{re} , annual repair cost of the i th component (in dollars) ; TC_i^{ENS} , annual energy not supply cost of the i th component (in dollars); TC_i^{hr} , annual human resources cost of the i th component (in dollars); TC_{PM} , total cost of preventive maintenance (in dollars); U_i , annual outage duration of the i th component (in minutes); TCM , total cost of maintenance (in dollars); X_{ij} , element of the i th row and j th column of the decision matrix in the TOPSIS method; α, β, γ , weight coefficients related to λ, U, ENS in the reliability improvement index; λ_i , annual failure rate of the i th component (in interruption per year); $\lambda_i^{base}, U_i^{base}, ENS_i^{base}$, λ, U, ENS of the i th component for allocating a PM budget equally to all the critical components; λ_i^{max} , maximum annual failure rate of the i th component (in interruption per year); λ_i^{min} , minimum annual failure rate of the i th component (in interruption per year);

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