Pareto Optimal Calculation and Simulation of XLPE Power Cable Production Line by Elitist Nonsorting Genetic Algorithm (NSGA-II)

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A special sorting genetic algorithm is used for optimization of catenary continuous vulcanization (CCV) line parameters in producing a specific power cable. Both production line speed and tube temperature profile are determined, but XLPE cure percent and outer insulation surface temperature are considered as objectives that must be optimum, simultaneously.

Over 50 years ago, polyethylene was introduced as an insulation material for electrical power cable. Polyethylene's inherent characteristics of toughness, resistance to chemicals and moisture, low temperature flexibility and excellent electrical properties, along with low cost and easy processability, make it a very desirable material for insulating low, medium and high-voltage electric cables[1].

During the process of manufacturing power cable insulated with cross-linkable polyethylene, the hot polymer is applied to the conductor by extrusion at temperatures under those of rapid vulcanization. The insulated core passes into a high-pressure tube to increase the temperature of insulation to the level at which the vulcanization agent is highly active. This is the continuous vulcanization (CV) tube. Therefore, changes of process variables associated with the CV tube may cause alteration in physical properties, ageing characteristics and heat resistance. The performance of the insulating compound in this area of crosslinking process may determine the maximum output rates of a power cable manufacturing facility[2].

In this article, a fast and elitist nondominated sorting genetic algorithm (NSGA-II) is used for multi-objective optimization of a medium and high-voltage cable production line for producing one specific power cable (500 mm^2 CU 132 KV). The conflicting objective functions that have been considered for minimization are, namely, uncrosslinked degree of insulation ($1 - r_p$) and temperature of outer surface of insulation(T_{out}). The design variables used in this optimization are, namely, temperature profile of cure tube (T_s) and production speed (v). For verifying this calculation, after performing optimization and calculating the Pareto Front, one design variable of optimization was selected as a desired production parameters and applied to the production line for extruding the specific cable's insulation. Then for determining whether or not the depending mechanical properties are fully realized after crosslinking, the hot set test was performed in prepared test samples from the produced cable on some insulated layers.

XLPE Power Cable Production Lines

Catenary continuous vulcanization (CCV) is one of the common XLPE power cable production lines in industry as its scheme is represented in **Figure 1**. In this case, a heating zone is followed by a cooling phase with water or pure nitrogen gas. These two zones are manufactured as continuous tube and in its first part, crosslinking of XLPE is obtained by dry curing under nitrogen high pressure. The XLPE insulation process starts in triple extruders where the conductor is coated with three layers as inner semi-conductor, XLPE insulation and outer semiconductor, respectively. Then the cable enters the heating tube that is filled with nitrogen at high pressure and high temperature profile in its specific zones. After that, the cable enters the cooling part of tube that is filled with water that its temperature is set between 18°C and 22°C and cable cools by water at 10 bar pressure. Finally the cable comes out from the tube and its cooling process is proceeded in the surrounding air by free convection.

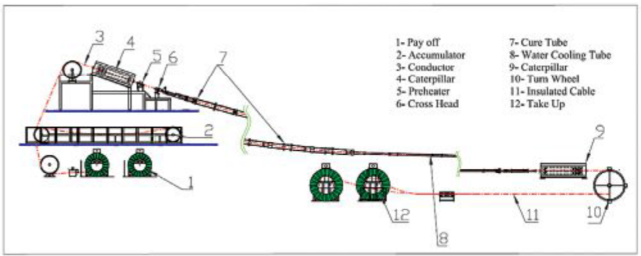

Fig. 1 — Schematic of CCV (continuous catenary vulcanization) power cable production line.

In the peroxide-cure process, heat and pressure can be applied by circulating high-temperature, high-pressure and generally, dry nitrogen through the steel curing tube. The nitrogen gas temperature is of the order of 300°C to 450°C at a pressure of 10 bar. The heat required to raise the temperature in the curing zone can be obtained from high-temperature nitrogen or radiant heater fixed on the outer side of the tube. The elevated temperature causes the peroxide to react and form the cross linked structure. The heat provided to the insulation causes the peroxide to be decomposed, generating volatiles such as acetophenone, methane, water vapor and alpha-methyl styrene[3]. The high pressure causes the gasses released in the crosslinking process to remain in the molten polymer so they do not form void that might lead to partial discharge and deterioration of the cable insolation. This pressure needs to be maintained until the entire insulation (cross-linked) gets solidified sufficiently to exit the tube[2,4,5].

To determine temperature profile and line speed, the following factors are to be considered:

- The heating and cooling are accomplished by heat transfer through insulation.
- The line speed affects the temperature profile.
- The time/temperature profile of the insulation should be sufficient to crosslink the insulation.

- Curing is not always completed in the heating zone. Part of the curing occurs in the cooling zone.
- The time in the cooling zone should be sufficient to reduce both the surface and the conductor temperature. Generally, when cable exits the CV tube, the conductor remains hotter than the surface and insulation. Care should be taken to maintain the quality.
- As noted previously, heat transfer occurs through surface. Therefore, to achieve the optimum throughput, the surface achieves very high temperature. An important consideration is that this temperature should not be so high as to cause problem for the performance of the cable. Thus, it is a universal practice to set a maximum permitted surface temperature. This becomes more critical due to semi-conducting layer. Well-designed materials are able to withstand temperatures as high as 275°C. But the normal range is from 250°C to 275°C[6].

Cross-Linked Reaction

Polyethylene is thermoplastic in nature and therefore can be reprocessed repeatedly. However, it will soften and flow, and lose critical physical properties at elevated temperature thereby limiting its application. Therefore crosslinking of polyethylene is carried out to retain desirable properties at high temperature. Crosslinking will change the nature of polymer from thermoplastic to thermoset to yield a nonmelting, more durable polymer matrix. Crosslinking leads to the formation of insoluble and infusible polymers in which polymer chains are joined together to form three-dimensional network structures. In thermoset, crosslinking (curing) takes place through reaction between polymer chains and several functional groups. These functional groups are capable of forming chemical bonds to convert thermoplastics into thermosets[7].

The most widely used technique for the insulation material curing is a crosslinking of polyethylene with organic peroxides. These peroxides (e.g., Dicumyl Peroxide, DCP) decompose at elevated temperature and pressure to liberate free radical that will abstract a hydrogen atom from the polymer chain. This abstraction site then becomes a reactive radical, forming a crosslinked bond with another reactive radical of same or different chain. This reaction occurs until all peroxide is consumed or the temperature falls below the decomposition point[4]. The chemical process of PE cross-linking by DCP in the presence of antioxidant is illustrated in **Figure 2**.

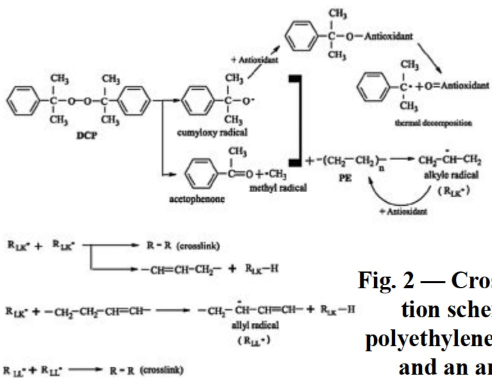

Fig. 2 — Crosslinking reaction scheme for the polyethylene with the DCP and an antioxidant.

The curing reaction of a thermoset polyester was investigated by using the isothermal and dynamic techniques of differential scanning calorimetry (DSC)[8]. The heats of reaction (at different curing temperatures) and a kinetic expression of the crosslinking reaction are reported in several studies. A mathematical expression for the curing reaction that could fit all of the experimental data has been developed from studies of different proposed kinetic models[9]. In this article, a kinetic equation of the following form was used:

$$\frac{dP}{dt} = kP^{a}(1-P)^{b} \tag{1}$$

Where parameters a and b are constants independent of temperature, k is rate constant, given by Arrhenius equation:

$$k = A_r exp\left(-\frac{E_a}{R_g T}\right) \tag{2}$$

Mathematical Model of the Process

For governing the mathematical model for the vulcanization process in CV line, the process can be considered in three separated parts as[4]:

- Heated part of the tube.
- Water cooled part of the tube.
- Air cooled part of CV line.

In all phases, the mathematical model is represented with a set of partial differential equation (PDE) and solved numerically by method of line (MOL) for chosen and initial conditions[10].

Mathematical modeling of the heated part:

By considering a cable composed by a conductor and insulation and due the axial symmetry of the problem, it is possible to model the process by means of only two independent variables, i.e., the distance r of a layer in the insulator with respect to cable axis and exposition time t. Because the velocity of cable u, is constant, a cable section at a distance z with respect to the starting point of the production line is characterized by an exposition time, meaning that z is a dependent variable.

In this part of the tube, the cable is surrounded by pure nitrogen in eight zones where all walls are heated by spiral heaters. All zone temperatures are set individually based on the process parameters. The heat is transferred from nitrogen to cable surface by convection due to the cable moving, radiation because of energy dissipation from steel tube wall to cable and conduction across the cable. Beside these mentioned heat transferred phenomena, since XLPE crosslinking is an exothermic chemical reaction, its reaction heat is released in insulation during crosslinking. By considering some assumptions as the temperature gradient in the axial direction of cable is neglected and the only radial heat conduction through the cable will be considered in the calculation and also by assuming that the thermodynamic properties (ρ,λ,C_P) are considered constant in all temperature range, the following mathematical model will be extracted by a set of PDEs:

— Material balance for the cable insulation part:

$$u\rho_p \frac{\partial P}{\partial z} - r_p = 0 \qquad (3)$$

Where, P and r_p are the degree of crosslinking and the rate of crosslinking respectively.

—Kinetic model for the crosslinking reaction occurred in the polymer:

$$r_p = A_r exp\left(-\frac{E_a}{R_g T}\right)(1-P)^m \qquad (4)$$

Where A_r, E_a, R_g and m are Arrhenius number, activation energy, gas constant and kinetic constant, respectively.

—Heat balance for the cable conductor:

$$u\rho_j c_{pj}\frac{\partial T_j}{\partial z} - \lambda_j\left[\frac{\partial^2 T_j}{\partial r^2} + \frac{1}{r}\frac{\partial T_j}{\partial r}\right] = 0 \qquad (5)$$

—Heat balance for the insulation:

$$u\rho_P c_{pP}\frac{\partial T_P}{\partial z} - \lambda_P\left[\frac{\partial^2 T_P}{\partial r^2} + \frac{1}{r}\frac{\partial T_P}{\partial r}\right] + \Delta H_r r_P = 0 \qquad (6)$$

ΔH_r is the insulation specific heat of reaction (enthalpy) that represents the bone breaking between oxygen-oxygen in the peroxide.

For solving these sets of partial differential equations, it is necessary to specify some auxiliary conditions to complete the statements of equations. Since the heat equations for insulation and conductor are of second order in space, hence two boundary conditions must be considered for each equation as:

—Because of symmetry condition on temperature field, at $r = 0$, for all z:

$$\frac{\partial T}{\partial r} = 0 \qquad (7)$$

—Whereas at $r = R$, for all z:

$$h(T_{z,R} - T_N) + q_{rad} = -\lambda_P\frac{\partial T}{\partial r} \qquad (8)$$

Where h denotes the heat transfer coefficient between XLPE and nitrogen, T_N is the nitrogen temperature and q_{rad} is the heat flux transferred by radiation between two cylindrical cable outer surface in temperature T_1 and inner side of cure tube wall in temperature T_2, which can be evaluated applying the following formula:

$$q_{rad} = \frac{\sigma A_1(T_1^4 - T_2^4)}{(1/\epsilon_1) + \left((A_1/A_2)((1/\epsilon_2)-1)\right)} \qquad (9)$$

Where σ is Stefan-Boltzmann constant, ϵ_1 and ϵ_2 are the emissivity coefficient of cable surface and the inner side of tube wall respectively, A_1 and A_2 are also the area of cable surface and the inner side of tube wall surface respectively.

—Finally, at the interface between conductor and insulation, heat flux exchanged is in equilibrium, meaning that at $r = d$, for all z:

$$\lambda_P\frac{\partial T_P}{\partial r} = \lambda_j\frac{\partial T_j}{\partial r} \qquad (10)$$

—For transient condition, heat equations and material balance equation are of first order in length, requiring the assumption of some initial conditions:

$$P(0, r-d) = 0 \qquad (11)$$

$$T_j(0, d) = T_j^0 \qquad (12)$$

$$T_P(0, R-d) = T_P^0 \qquad (13)$$

Mathematical modeling of the water cooled part:

Since the temperature of cable is in its maximum limit and is very vulnerable to be damaged by contacting the other metal or hard elements of the production line, reducing this temperature to around 80°C is necessary. To do this, the cable enters the water cooling zone after exiting the heating zone and passing a short neutral zone.

The cooling water flows counter-current inside the tube, and from the calculated Reynolds number, it can be assumed a turbulent flow regime. By assuming that the temperature of the cold water in the tube is constant in radial direction, and it changes only in the axial direction, the mathematical model for this part of the process can be considered as the previous equations with new boundary conditions in cable surface-water interface that is defined by:

$$\frac{\partial T_P}{\partial r} = -\frac{h_{H_2O}}{\lambda_P}\left(T_P - T_{H_2O}\right) \qquad (14)$$

Where T_{H_2O} is the water temperature and h_{H_2O} is the water heat transfer coefficient that is calculated from well-known empirical correlation based on forced convection in tubular water flow as[11]:

$$Nu = 0.023 Re^{0.8} Pr^n \quad \begin{cases} n = 0.4\ for\ heating \\ n = 0.3\ for\ cooling \end{cases} \qquad (15)$$

Where Pr is Prandtl number, Re is Reynolds number and Nu is Nusselt Number. This equation is valid for fully developed turbulent flow in smooth tubes for fluids with Prandtl number ranging from about 0.6 to 100 and with moderate temperature differences between wall and fluid condition. These dimensionless numbers are calculated as:

$$Re = \frac{\rho u d}{\mu}\ ,\quad Pr = \frac{C_p \mu}{\lambda}\ ,\quad Nu = \frac{hd}{\lambda} \qquad (16)$$

Then: $$h = \frac{Nu\,\lambda}{d} \qquad (17)$$

Mathematical modeling of the air cooled part:

After the cable passes the entire cooling part of tube and goes out through the water end seal, it is cooled by natural convection in the surrounding air until the end of the line when the product is wound onto the reel. Although the most part of cable heat is dissipated in the water cooling part of tube until the cable temperature at the end of tube shouldn't exceed 90°C, but because of existing temperature gradient inside the cable and the possibility of increasing the cable temperature, it is necessary to consider enough distances between water end seal and take up for having enough time for proper cooling by surrounding air convection. For preventing mechanical damage and insulation deformation when it is wound on the reel, it is recommended the cable temperature shouldn't exceed more than 50°C.

The cable can be considered as a heat exchanger with radial heat conduction across the cable (radial direction) and free convection from the cable surface to the surrounding air. The mathematical model will be also a set of partial differential equations the same as previous equations with a new boundary condition of heat transfer from the cable surface to the air as:

$$\frac{\partial T_P}{\partial r} = -\frac{h_{air}}{\lambda_P}(T_P - T_{air}) \qquad (18)$$

Where T_{air} is the air temperature and h_{air} is the air heat transfer coefficient that is calculated from well-known empirical correlation based on free convection from horizontal cylinder:

$$N_u = \frac{hd}{\lambda_{air}} = C(Gr.Pr)^m \qquad (19)$$

Where *Gr* is Grashoff number, *C* and *m* are functions of air flow that should be taken from literature for the given multiplier (*Gr.Pr*). The calculated heat transfer coefficient for different estimated temperatures ranges from 6.43 and 8.34 $W\,m^{-2}\,K^{-1}$. During the calculation, mean value of *h* was considered.

Multi-Objective Pareto Optimization

Multi-objective optimization, which is also called multi-criteria optimization or vector optimization, has been defined as finding a vector of decision variables satisfying constraints to give acceptable values to all objective functions. These functions form a mathematical description of performance criteria, which are usually in conflict with each other. Hence, the term "optimization" means finding such a solution, which would give the values of all the objective functions acceptable to the designer[12-14]. In general, it can be mathematically defined as find the vector $X^* = [x^*_1, x^*_2 \ldots x^*_n]$ to optimize $F(X)=[f_1(X), f_2(X) \ldots f_k(X)]^T$ subject to m inequality constraints $g_i(X) \leq 0$ i=1 to m, and p equality constraints $h_j(X)=0$ j=1 to p, where the $X^* \in R^n$ is the vector of decision or design variables, and the $F(X) \in R^k$ is the vector of objective functions, which must each be minimized or maximized. But without loss of generality, it is assumed that all objective functions are to be minimized. Such multi-objective minimization based on Pareto approach can be conducted using some more definitions as:

Definition of Pareto dominance:

A vector $U=[u_1, u_2, \ldots u_k] \in \mathcal{R}^k$ is dominate to vector $V=[v_1, v_2, \ldots v_k] \in \mathcal{R}^k$ (denoted by $U \prec V$) if and only if:

$$\forall i \in \{1,2,\ldots,k\}, u_i \leq v_i \ \wedge \exists j \in \{1,2,\ldots,k\}: u_j < v_j \, .$$

In other words, there is at least one u_j which is smaller than v_j whilst the remaining *us* are either smaller or equal to corresponding *vs*.

Definition of Pareto optimality:

A point $X^* \in \Omega$ (Ω is a feasible region in $\mathcal{R}^n$ satisfying equality and inequality constraints) is said to be Pareto optimal (minimal) with respect to all $X \in \Omega$ if and only if $F(X^*) \prec F(X)$. Alternatively, it can be readily restated as:

$$\forall i \in \{1,2,\ldots,k\}, \forall X \in \Omega - \{X^*\}\ f_i(X^*) \leq f_i(X) \wedge \exists j \in \{1,2,\ldots,k\}: f_j(X^*) < f_j(X).$$

In other words, the solution X^* is said to be Pareto optimal (minimal) if no other solution can be found to dominate X^* using the definition of Pareto dominance.

Definition of a Pareto set:

For a given MOP, a Pareto set $\mathcal{P}^*$ is a set in the decision variable space consisting of all the Pareto optimal vectors:

$$\mathcal{P}^* = \{X \in \Omega \,|\, \nexists X' \in \Omega : \mathrm{F}(X') \prec F(X)\}$$

In other words, there is no other X' as a vector of decision variable in Ω that dominate any $X \in \mathcal{P}^*$.

Definition of a Pareto front:

For a given MOP, the Pareto front $\mathcal{PF}^*$ is a set of vector of objective function, which are obtained using the vectors of decision variables in the Pareto set $\mathcal{P}^*$, that is $\mathcal{PF}^*=\{F(X)=(f_1(X), f_2(X), \ldots f_k(X)) : X \in \mathcal{P}^*\}$. In other words, the Pareto front $\mathcal{PF}^*$, is a set of the vectors of objective functions mapped from $\mathcal{P}^*$.

In this article, one of an improved version of NSGA, which is called NSGA-II is used for solving the present multi objective optimization problem. From the simulation results on a number of difficult test problems, it is proved that NSGA-II outperforms two other contemporary multi-objective EAs-Pareto-archived evolution strategy (PAES),[12] and strength Pareto EA (SPEA)[22]—in terms of finding a diverse set of solutions and in converging near the true Pareto-optimal set.

Elitist Non-dominated Sorting Genetic Algorithm (NSGA-II)15:

In this approach, every solution from the population is checked with a partially filled population for domination. To start with, the first solution from the population is kept in a set P'. Thereafter, each solution P (the second solution onwards) is compared with all members of the set P' one by one. If the solution P dominates any member q of P', then solution q is removed from P'. This way nonmembers of the nondominated front get deleted from P'. Otherwise, if solution P is dominated by any member of P', the solution P is ignored. If solution P is not dominated by any member of P', it is entered in P'. This is how the set P' grows with nondominated solutions.

When all solutions of the population are checked, the remaining members of P' constitute the nondominated set.

$P' =$ find-nondominated-front (P)
$P' = \{1\}$
  For each $p \in P \ \wedge p \notin P'$
$P' = P' \cup \{p\}$
  For each $q \in P' \wedge q \neq p$
  If $p \prec q$, then $P' = P' \setminus \{q\}$
  Else if $q \prec p$ then $P' = P' \setminus \{p\}$

To find other fronts, members of P' will be discounted from P and the above procedure is repeated, as outlined:

$\mathcal{F}$ = fast-non-dominated-sort (P)
$i = 1$
Until $P = \emptyset$
$\mathcal{F}_i$ = find-nondominated-front (P)
$P = P \backslash \mathcal{F}_i$
$i = i + 1$

At the end of this operation, solutions of the first nondominated front are stored in $\mathcal{F}_1$, solutions of the second nondominated front are stored in $\mathcal{F}_2$, and so on.

To estimate of the density of solutions surrounding a particular solution in the population, the average distance of two points on either side of this point along each of the objectives is calculated. This quantity $i_{distance}$ serves as an estimate of the size of the largest cuboid enclosing the point i without including any other point in the population (crowding distance).

Crowding distance computation requires population sorting according to each objective function value in their ascending order of magnitude. Thereafter, for each objective function, the boundary solutions (solutions with smallest and largest function values) are assigned an infinite distance value. All other intermediate solutions are assigned a distance value equal to the absolute difference in the function values of two adjacent solutions. This calculation is continued with other objective functions. Overall crowding distance value is calculated as the sum of individual distance values corresponding to each objective. The following algorithm outlines crowding distance computation procedure of all solutions in a nondominated: set I:

Crowding-distance- assignment (I)
$l = |\mathrm{I}|$
For each i, set $\mathrm{I}[i]_{distance} = 0$
For each objective m
$\mathrm{I} = \mathrm{sort}\ (\mathrm{I}, m)$
$\mathrm{I}[1]_{distance} = \mathrm{I}[l]_{distance} = \infty$
for $i = 2$ to $(l - 1)$
$\mathrm{I}[i]_{distance} = \mathrm{I}[i]_{distance} + (\mathrm{I}[i+1] \cdot m - \mathrm{I}[i-1] \cdot m)$

Here $\mathrm{I}[i] \cdot m$ refers to the *m-th* objective function value of the *i-th* individual in the set I.

After all population members in the set I are assigned a distance metric, it is possible to compare two solutions for their extent of proximity with other solutions. A solution with a smaller value of this distance measure is, in some sense, more crowded by other solutions. This is exactly what is suitable for comparing in the proposed crowded comparison operator.

The crowded comparison operator ($\prec_n$) guides the selection process at the various stages of the algorithm towards a uniformly spread-out Pareto-optimal front. Assume that every individual i in the population has two attributes:

1. Non-domination rank (i_{rank}) and
2. Crowding distance($i_{distance}$).

We now define a partial order $\prec_n$ as:

$$i \prec_n j \text{ if } (i_{rank} < j_{rank}) \text{ or } ((i_{rank} = j_{rank}) \text{ and } (i_{distance} > j_{distance}))$$

That is, between two solutions with differing non-domination ranks, the solution with the lower (better) rank is preferred. Otherwise, if both solutions belong to the same front, then the solution which is located in a lesser crowded region is preferred.

After describing the fast nondominated sort procedure and density estimation, it is now possible to present the main loop of the algorithm.

Initially, a random parent population P_0 is created. The population is sorted based on the nondomination. Each solution is assigned a fitness (or rank) equal to its nondomination level (1 is the best level, 2 is the next-best level and so on). Thus, minimization of fitness is assumed. At first, the usual binary tournament selection, recombination, and mutation operators are used to create a child population Q_0 of size N. Since elitism is introduced by comparing current population with previously found best nondominated solutions, the procedure is different after the initial generation. A generation of the proposed algorithm is described as:

$R_t = P_t \cup Q_t$
$\mathcal{F}$ = fast-non-dominated-sort (R_t)
$P_{t+1} = \emptyset$ and $i = 1$
Until $|P_{t+1}| + |\mathcal{F}_i| \le N$
crowding-distance-assignment $(\mathcal{F}_i)$
$P_{t+1} = P_{t+1} \cup \mathcal{F}_i$
$i = i + 1$
sort $(\mathcal{F}_i, \prec_n)$
$P_{t+1} = P_{t+1} \cup \mathcal{F}_i[1:(N - |P_{t+1}|)]$
Q_{t+1} = make-new-pop(P_{t+1})
$t = t + 1$

The above step-by-step procedure shows that NSGA-II algorithm is simple and straightforward. First, a combined population $R_t = P_t \cup Q_t$ is formed. The population R_t will be of size 2N. Then, the population R_t is sorted according to nondomination. Now, solutions belonging to the best nondominated set $\mathcal{F}_1$ are of best solutions in the combined population and must be emphasized more than any other solution in the combined population. If the size of $\mathcal{F}_1$ is smaller than N, we definitely choose all members of the set $\mathcal{F}_1$ for the new population P_{t+1}. The remaining members of the population P_{t+1} is chosen from subsequent nondominated fronts in the order of their ranking. Thus, solutions from the set $\mathcal{F}_2$ are chosen next, followed by solutions from the set $\mathcal{F}_3$, and so on. This procedure is continued till no more sets can be accommodated.

Let us say that the set $\mathcal{F}_l$ is the last nondominated set beyond which no other set can be accommodated. In general, the count of solutions in all sets from $\mathcal{F}_1$ to $\mathcal{F}_l$ would be larger than the population size. To choose exactly N population members, we sort the solutions of the last front using the crowded comparison operator $\prec_n$, in the descending order and choose the best solutions needed to fill all population slots. The NSGA-II procedure is also shown in **Figure 3**.

It is important to note that the binary tournament selection operator is used, but the selection criterion is now based on the crowded comparison operator $\prec_n$. Since this operator requires both the rank and crowded distance of each solution in the population, these quantities are calculated while forming the population P_{t+1}, as shown in the above algorithm.

Numerical Simulation

The complexity of XLPE extrusion process and the enor-

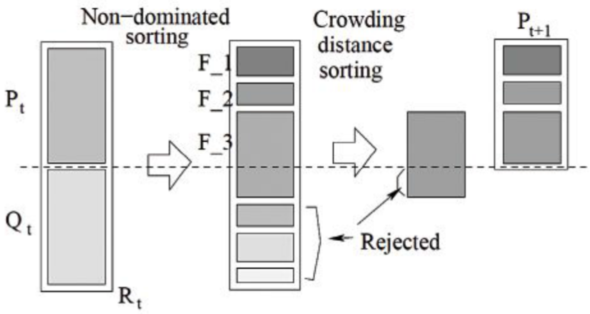

Fig. 3 — A sketch of NSGA-II.

mous amount of process parameters involved make it difficult to keep the process under control. The complexity and parameter manipulation may cause serious quality problems and high manufacturing costs[16]. One of the main goals of XLPE extrusion is the improvement of quality of insulation mechanical and electrical properties. Better insulation properties considerably improve the grade of dielectric strength of insulation and prolong the life time of cable.

In term of production quality, during the heating and curing cycles in the tube, some requirements should be satisfied. First at the end of the process, the degree of uncross linking should be minimum through the insulation layer. On the other hand, manufacturing experiences proves that for reducing the ovality of insulation, it is preferred to cure XLPE in the lowest temperature as possible in the tube.

In this section, a fast non-dominated sorting genetic algorithm (NSGA-II) presented in the previous section is used for multi objective design of CCV line for producing specific XLPE cable (500 mm^2 CU 132 KV). In this optimization the temperature profile of cure tube (T_s) and production speed (v) NSGA-II algorithm whereas two conflicting objective functions as uncross linked degree of insulation ($1\text{-}r_p$) and temperature of outer surface of insulation (T_{out}) should be minimum simultaneously. A population of 80 individuals with a crossover probability of 0.9 and mutation probability of 0.1 has been used in 240 generations. In this simulation, Pareto fronts of this pair of two objectives have been shown through **Figure 4**. It is clear from this figure that obtaining a better value of one objective would normally cause a worse value of another objective. However, if the set of decision variables is selected based on each of a Pareto front, it will lead to the best possible combination of that pair of objectives. It should be noted that all the optimum design points in this Pareto front are non-dominated and could be chosen by a designer. It is clear from this figure that choosing a better value for any objective functions in this Pareto front would cause a worse value of another objective function.

For illustrating the feasible search space, some numbers of random feasible solutions are created and plotted with 'dots' on the plot as shows the Pareto front together in **Figure 5**.

It is clear that if any decision variables of this set is chosen, the corresponding values of pair of objectives will locate a point inferior to the corresponding Pareto front. Such inferior area in the space of the objective functions for **Figure 4** are in fact top/ right sides.

Based on cable manufacturer's practical experience, the proper XLPE crosslinking quality would be achieved by considering the uncross-linked degree less than 0.05 and the process engineers will calculate and set the temperature profile of cure tube and line velocity for assuring the insulation proper crosslinking. By satisfying this very practical important point and by considering this fact that for preventing the ovality problem during the cross linking reaction, the temperature of outer surface of insulation should be minimum.

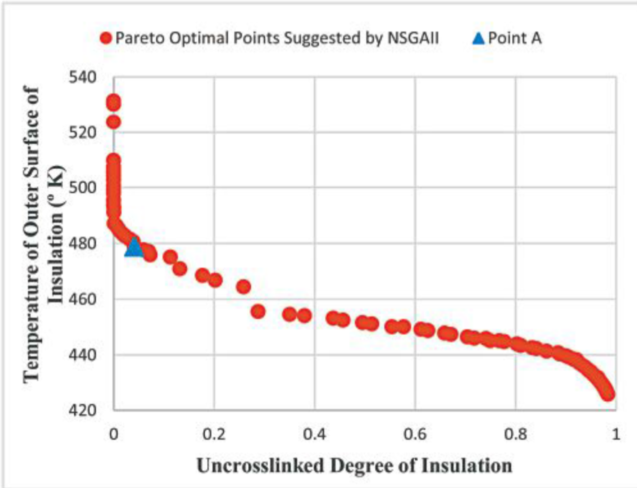

Fig. 4 — Pareto front and selected point A.

For more investing the mathematical model in capabilities of modeling the continuous crosslinking process, the simulation is performed based on the design variables that are related to the one of Pareto front solutions. This point as depicted as point A in **Figure 4** is selected by considering two previous mentioned criteria as minimum both uncrosslinked degree and the temperature of outer surface of insulation. Several figures are included to demonstrate the effect of process operating variables and cable construction on the degree of crosslinking and temperatures in the cable.

Figure 6 shows the temperature radial profiles inside the cable as a function of the tube length in several radial positions. At the first 38 meter in the heated part of the tube, the temperature rises across the cable diameter with the maximum on the cable surface. In the next part of tube, the cable enters

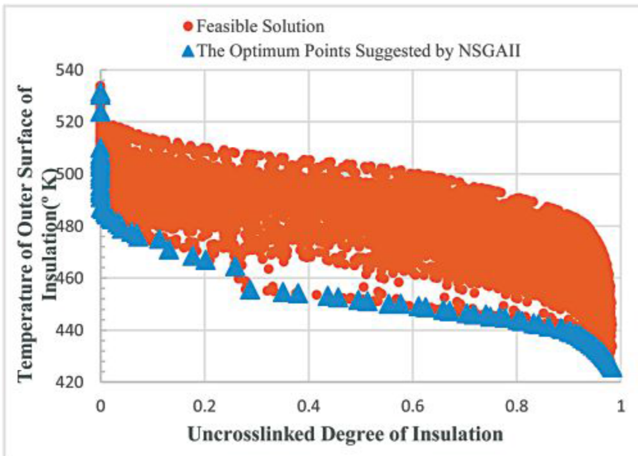

Fig. 5 — Pareto optimal solution with NSGA-II on feasible range.

the water cooled part of tube. As it is cleared, because of the proper water cooling capacity, the temperature of cable is starting to decrease and at the end of this part after 137 m the temperature of cable is 27ºC on the surface of cable. The last part of process is the cable cooling in the surrounding air after the water cooled part. Finally after 240 m of the process, the temperature of the cable is decreased to the ambient temperature at around 25ºC and it must be equal across the whole radius.

Figure 7 shows the degree of cross linking (r_p) of insulation along the production tube at five different positions in the radial direction of cable. As it is cleared because of high temperature gradient in layers that are close to the outer surface of cable, the degree of cross linking reaches 0.95 sooner than that layers that are located near the conductor.

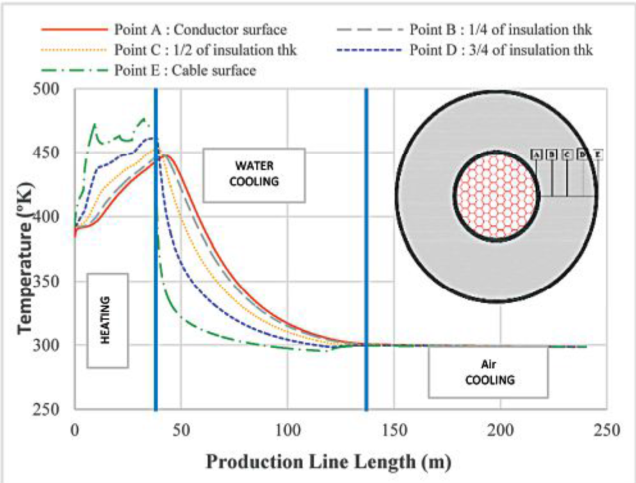

Fig. 6 — Calculated temperature profiles along the whole production line at different cable radial positions.

Although the outer layers of insulation are going to be cool when the cable goes in to the water cooling zone, the temperature gradient increases the temperature of layers that are close to the conductor. For this reason after passing some meters in the cooling zone, the degree of crosslinking should be completely equalized across the insulation.

Figure 8 and **Figure 9** depict the radial degree of crosslinking and temperature profile inside the cable in some positions of cure tube respectively. Since the heat transfers from the hot tube wall and hot nitrogen to the insulation surface by the radiation and convection phenomena and then transfers inside the cable by conduction, the temperature rises from the cable center to the insulation's outer surface. On the other hand because of high thermal conductivity of copper, the temperature is nearly constant in all conductor section.

Practical Results

In order to verify the optimization and simulation results, a production as a test was also conducted as the temperature of production cure tube zones and the production line speed are set exactly the design variable related to point A.

As it was mentioned before, the insulation physical and mechanical properties completely rely on the degree of crosslink parameter. A hot set test is used as a means for determining

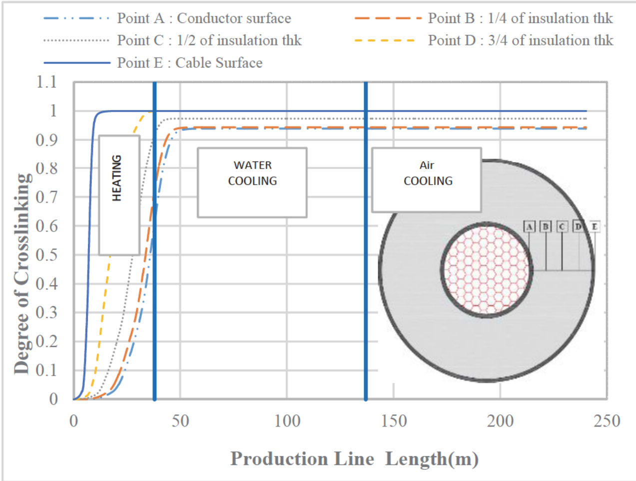

Fig. 7 — Calculated degree crosslinking along the whole production line at different cable radial positions.

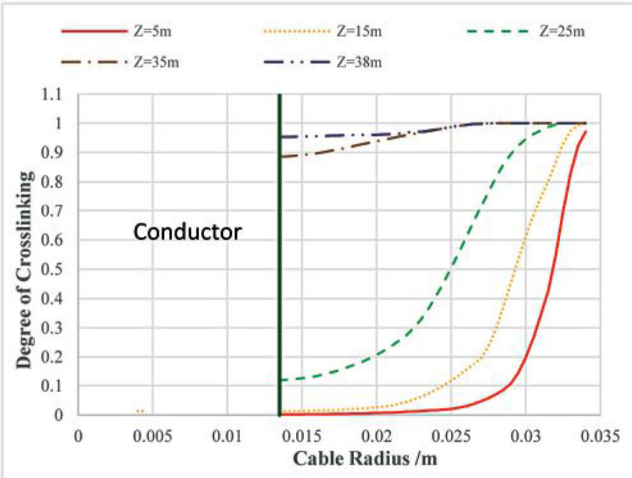

Fig. 8 — Calculated degree crosslinking through the cable (r) at different positions in the tube (z).

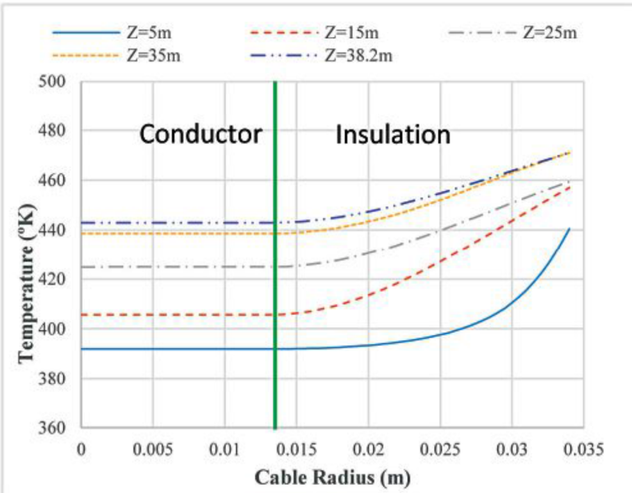

Fig. 9 — Calculated radial temperature profiles through the cable (r) at different position in the tube (z).

whether or not the depending properties are fully realized after crosslinking. In this test, the elongation of the insulating material at an elevated temperature under the action of a specified tensile load and its recovery after removal of the load are determined to evaluate the efficiency of the cross-linking. A dumbbell of specified shape and size is suspended from a vertical frame inside a hot air oven with a specified load suspended from its lower end. The elongation of the test specimen after some 15 minutes under the above conditions and its subsequent recovery after removal of the load are then evaluated. the temperature for testing for XLPE cables is 200°C ±3°C under load for 15 minutes and mechanical stress of 20 N/cm^2, elongation under load is 175% maximum and permanent elongation is not more than 15%.

Figure 10 shows the specimen that is prepared for hot set test and the elongation is 55% and the permanent elongation result is 0% that had proved the excellent crosslinking of the produced cable.

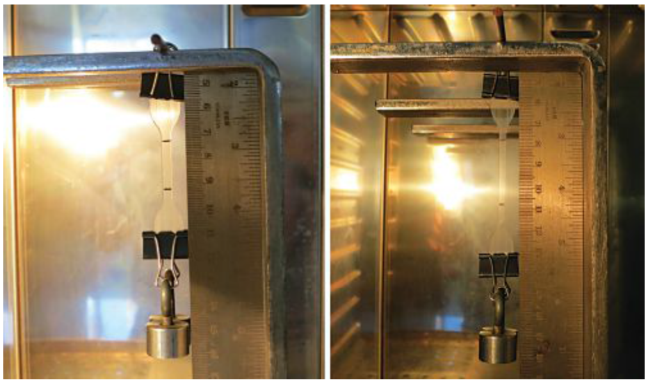

Fig. 10 — Specimen prepared for hot set test.

Conclusion

The NSGA-II elitist nondominated sorting genetic algorithm has been successfully used for optimal analysis of specific XLPE power cable production in a continuous catenary vulcanization line for determining temperature profile of cure tube (T_s) and production speed (v).

In this analysis of XLPE power cable production, the objective functions that conflict with each other were selected as uncrosslinked degree of insulation ($1\text{-}r_p$) and temperature of outer surface of insulation (T_{out}).

The advantage of the obtained optimum design points was verified by performing a hot set test on the cable that was produced with the optimum production speed and optimum temperature of cure tube.

To have further discussion, contact the author at **SIMCO (P, J, S, C)** in Iran or visit: *www.simcocable.com*

References:

1. *M. W. Aarts, J. B. Kjellqvist, A. Mendelsohn, and K. Vaterrodt, "The performance of XLPE water tree resistant insulation systems against the requirements of DIN VDE 0276–605/A3," CIRED 2005 - 18th International Conference and Exhibition on Electricity Distribution. pp. 1–5, 2005.*
2. *V. Kosar, Z. Gomzi, and K. Šintić, "Modelling and simulation of the continuous power cable processing," Chem. Eng. Process. Process Intensif., vol. 46, no. 2, pp. 83–88, 2007.*
3. *W. Andrews, Tim and Hampton, RN and Smedberg, Annika and Wald, D and Waschk, V and Weissenberg, "The role of degassing in XLPE power cable manufacture," IEEE Electr. Insul. Mag., vol. 22, no. 6, pp. 5–16, 2006.*
4. *V. Kosar and Z. Gomzi, "Modeling of the power cable production line," Thermochim. Acta, Vol. 457, Noi. 1, pp. 70–82, 2007.*
5. *G. Milani and F. Milani, "Optimization of power cable production lines for EPM/EPDM elastomers by genetic algorithm with different peroxides," J. Appl. Polym. Sci., vol. 111, no. 1, pp. 482–507, Jan. 2009.*
6. *J. Fothergill and R. Hampton, "Polymer insulated power cable," in Advances in High Voltage Engineering, The Institution of Engineering and Technology, Michael Faraday House, Six Hills Way, Stevenage SG1 2AY, UK: IET, pp. 477–510.*
7. *S. M. Tamboli, S. T. Mhaske, and D. D. Kale, "Crosslinked polyethylene," Indian J. Chem. Technol., vol. 11, no. 6, pp. 853–864, 2004.*
8. *G. Liang and K. Chandrashekhara, "Cure kinetics and rheology characterization of soy-based epoxy resin system," J. Appl. Polym. Sci., vol. 102, no. 4, pp. 3168–3180, 2006.*
9. *S. Y. Pusatcioglu, A. L. Fricke, and J. C. Hassler, "Heats of reaction and kinetics of a thermoset polyester," J. Appl. Polym. Sci., vol. 24, no. 4, pp. 937–946, 1979.*
10. *W. E. Schiesser and G. W. Griffiths, A Compendium of Partial Differential Equation Models : Method of Lines Analysis with Matlab. 2009.*
11. *J. P. Holman, Heat transfer, 8th ed. McGraw-Hill, 1989.*
12. *C. A. Coello Coello, "A Comprehensive Survey of Evolutionary-Based Multiobjective Optimization Techniques," Knowl. Inf. Syst., vol. 1, no. 3, pp. 269–308, 1999.*
13. *C. a. C. Coello and R. L. Becerra, "Evolutionary multiobjective optimization using a cultural algorithm," Proc. 2003 IEEE Swarm Intell. Symp. SIS'03 (Cat. No.03EX706), pp. 6–13.*
14. *N. Nariman-Zadeh, M. Salehpour, A. Jamali, and E. Haghgoo, "Pareto optimization of a five-degree of freedom vehicle vibration model using a multi-objective uniform-diversity genetic algorithm (MUGA)," Eng. Appl. Artif. Intell., vol. 23, no. 4, pp. 543–551, 2010.*
15. *K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," IEEE Trans. Evol. Comput., vol. 6, no. 2, pp. 182–197, 2002.*
16. *R. a Yadav, R. Scholar, P. S. V Joshi, and A. P. N. K. Kamble, "Recent Methods for Optimization of Plastic Injection Molding Process - A Literature Review," Int. J. Sci. Eng. Res., vol. 3, no. 12, pp. 1–8, 2012.*

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