An educational package for environmentally friendly, economic operation of power systems

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Abstract This paper presents a Windows™-based educational package developed by the authors to provide power systems students with basic training on the environmentally friendly, economic operation of power systems. The suitability of the package has been demonstrated here with the help of a six-generator thermal power system.

Keywords economic operation; package; power systems; training

In today's competitive environment, new power system engineers are expected to contribute immediately to the task, without some years of seasoning via on-the-job training, mentoring, and rotation assignments. So it is becoming necessary to prepare power system engineering graduates for an increasingly quality-minded corporate environment. In order to achieve this, there is a critical need to make available improved tools for educating and training power system engineering students. As a result of the rapid advances in computer hardware and software, many Windows™-based computer software packages[1–6] have been developed for the purpose of educating and training. Examples of such packages include power flow calculation, economic power dispatch, automatic load-frequency control, fault analysis, stability analysis, symmetrical component analysis, and system operator training.

In recent years, governments and the general public worldwide have started paying more attention to environmental protection. Since electric power industry emissions are a major cause of urban and rural ozone pollution, the power industries are to be re-engineered to meet the goal of a clean atmosphere. Both power systems engineering graduates and in-service system engineers are to be tuned and trained to cater for the environmental needs of the day.

The motivation for the development of the package 'Gen–Target' presented in this paper is to provide basic training for power system engineering students, on the following two main challenges: (i) economic operation of power systems to survive in the competitive market, and (ii) the generation of power with environmental constraints to meet environmental regulations. For the development of the package, a Windows™-based Graphical User Interface (GUI) is used, which gives the advantages of (i) interactive visual communication between users and computer processes, (ii) quick interpretation of test results, (iii) better understanding of the system conditions, system data, and dispatch outputs due to graphical display, and (iv) simplicity in operation due to the non-DOS environment.

Structure of Gen-Target

A working main screen appears as shown in Fig.1 when the user starts the package developed in Visual Basic. It consists of the title bar, menu bar, and six functional component blocks.

The functions of the menus are:

File: To do standard file storage or retrieve files for operations.
Input Data: To open data input form for data entry, where fuel cost coefficients and emission coefficients are entered for dispatching purposes.
Display/Clear Display: To display data on the working screen for analyzing the graphical display, and then to clear.
Calculate: This is the application calculation part; user has to click this after data entry, to view the dispatch outcome.
Close Data Form: Used to close the existing project data and to enter a new set of data for analyzing.
Print preview: This is an option provided for the user to view all the input as well as output information in a printable format, and from there the user can have printouts.
Setting: It is the user option to set the password for the application.

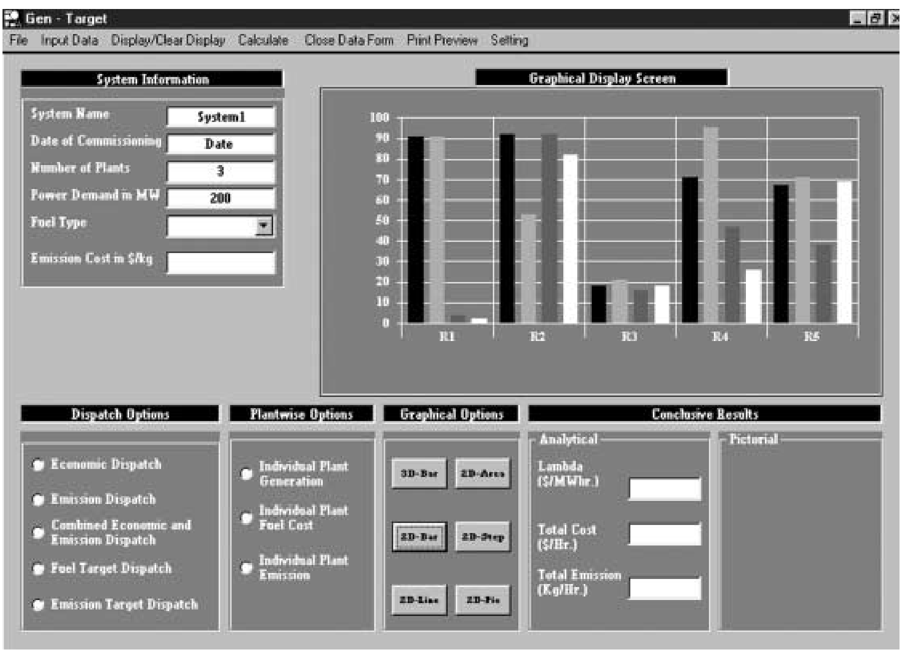

Fig. 1 *Working main screen.*

Then, the six functional components are:

System Information
Dispatch Options
Plantwise Options
Graphical Options
Conclusive Results, and
Graphical Display Screen.

The objectives, scope and functions of each of the components are briefly given in the following paragraphs.

System Information component

This component requires six items of information for identification of the power system, among which System Name and Date of Commissioning are optional. Information such as Number of Plants and Power Demand in MW are essential and if the user forgets to enter, default values appear. In order to choose the Fuel Type, a pull-down list box is provided. The information Emission Cost in $/kg is essential only for performing Combined Economic and Emission Dispatch.

Dispatch Options component

Economic Dispatch, Emission Dispatch, Combined Economic and Emission Dispatch, Fuel Target Dispatch, and Emission Target Dispatch are the various dispatch modules provided for the user under the Dispatch Options component. A radio button is provided for each module and the user can choose the particular option just by clicking on the respective button. Only one out of the given five modules can be selected for basic training at a time. A dialog box appears when additional data are to be entered. A validation is done for the proper format of the data.

Plantwise Options component

Under this output option, Individual Plant Generation, Individual Plant Fuel Cost, and Individual Plant Emission are the additional sub-output options provided for the user to know the individual plant's contribution on total generation, total cost, and total emission. A radio button is provided for each option and the user can choose the particular option just by clicking on the respective button. Only one out of the given three sub-output options can be selected at a time. The Plantwise Options can be viewed through the Graphical Display Screen.

Graphical Options component

The Graphical Options component is an output component, which provides six graphical sub-output options to review the system output. By clicking a command button, the user can select the graphical display type of interest. The system output display can be viewed through the Graphical Display Screen.

Conclusive Results

The essential key outputs are displayed in two different forms: analytical and pictorial. Both the forms of outputs are displayed simultaneously. The analytical outputs are displayed in the text boxes provided and the pictorial outputs are projected in the picture box. The pictorial view is a symbolic one and its significance is just to give a comparison on the amount of pollution and the amount of saving in cost, among the various dispatch options. For instance, if the saving in cost is more, a picture of a big bag with dollar logo appears in deep colours; if the saving is less, the bag becomes smaller in size and lighter in colour. Likewise, if the emission is less, a green scenery picture appears; if it is more, a picture of a smoky automobile appears.

Graphical Display Screen component

The Graphical Display Screen is another component of the package, which is specially provided to view the outcome of the Plantwise Options through the Graphical Options. This is a chart-type computer software object, programmed to display the output as per user's selection. If the user does not select any option, then a default display will appear as shown in Fig. 1. The display screen can be adjusted and the chart title can be conveniently placed within the screen area provided.

Basics of training module

As listed in the Dispatch Options, the user can obtain basic training on:

Economic Dispatch,
Emission Dispatch,
Combined Economic and Emission Dispatch,
Fuel Target Dispatch, and
Emission Target Dispatch modules.

Before proceeding to the actual training, it is better for the user to know the basic concept of each training module, and hence this section deals with the essential programming-related part only.

Economic Dispatch module

Economic power dispatch is a common problem pertaining to the allocation of the amount of power to be generated by different power plants in a system on an optimum economy basis. Mathematically, the economic dispatch problem is defined so as to minimize

$$F_{\mathrm{t}} = \sum_{i=1}^{n} \left(a_i P_i^2 + b_i P_i + c_i \right) \quad \$/\mathrm{h}; \quad i = 1, 2, ...n \tag{1}$$

where F_{t} is the total operating cost (mainly the fuel cost) of the thermal power system in \$/h, P_i is the power output of the ith generating plant in MW; a_i, b_i, and c_i are the fuel cost coefficients of the ith plant, and n is the number of thermal plants in operation. This optimization is subject to the usual equality and inequality constraints. Since the objective of the paper is only to offer basic training, the system transmission loss has not been considered, to maintain simplicity. Under such conditions, for a given power demand P_D, the solution of the objective function is directly given[7] in terms of the incremental cost of received power, λ, as

$$\lambda = \left(P_D + \sum_{i=1}^{n} b_i/2a_i\right) \Big/ \left(\sum_{i=1}^{n} 1/2a_i\right) \quad \$/\text{MW h} \tag{2}$$

and from which the individual plant generations, P_i, can be obtained straight away as

$$P_i = (\lambda - b_i)/2a_i \quad \text{MW} \tag{3}$$

Once the individual plant generations are known, the total operating cost of the power system, F_t in \$/h, and the corresponding emissions, E_t in kg/h, can be found. It can be seen that the total operating cost will be minimum and the corresponding emission level will be high, in this case.

Emission Dispatch module

Emission dispatch is the problem of minimizing the emissions of power systems whilst operating. Mathematically, the emission dispatch problem is defined so as to minimize

$$E_t = \sum_{i=1}^{n} \left(d_i P_i^2 + e_i P_i + f_i\right) \text{kg/h}; \quad i = 1, 2, \ldots\ldots n \tag{4}$$

where E_t is the total emission of the thermal power system in kg/h, P_i is the power output of the ith generating plant in MW; d_i, e_i, and f_i are the emission coefficients of ith plant, and n is the number of thermal plants in operation. The optimization algorithm is similar to the economic dispatch with the only change that fuel cost coefficients are replaced by emission coefficients. Once the individual plant generations are known, the total operating cost of the power system, F_t in \$/h, and the corresponding emission, E_t in kg/h, can be found. It may be noted that the total emission will be minimum and the corresponding operating cost will be high, in this case.

Combined Economic and Emission Dispatch module

The plants' generation schedules of Economic Dispatch (minimum cost) and Emission Dispatch (minimum emission) are considerably different. The minimum cost algorithm reduces the total operating cost of the system at an increased rate of emission, whereas the minimum emission algorithm reduces the total emission by an increase in system operating cost. Minimum emission is not always a demanded one; instead Generation Dispatch, which meets the stipulated environmental constraints, is rather more sensible than separate economic and emission dispatches. In the Combined Economic and Emission Dispatch algorithm, the emission costs are blended with the normal fuel costs with the use of a price penalty factor.[8] This avoids the use of two classes of dispatching (i.e. separate minimum cost and minimum emission dispatches) and the need for switchover between them. After introduction of the price penalty factor, the total operating cost of the system is the cost of fuel plus the implied cost of the emission, which can be optimized as discussed in Economic Dispatch module above.

Fuel Target Dispatch module

For a power system operating with n thermal plants in parallel to meet a system demand P_D, El-Hawary[9] represented the total operating cost of such n plants by a single equivalent cost function in terms of the cost functions of the individual plants and the power demand. This has been the basis for the proposed Fuel Target Dispatch.

If the total fuel cost, F_t, is specified as the operating target cost, then the corresponding system demand, P_D, that has to be shared by all the thermal plants operating in parallel, can be deduced by the use of Ref. [6] as

$$P_D = \left\{-B + \left[B^2 - 4A(C - F_t)\right]^{1/2}\right\} \Big/ (2A) \quad \text{MW} \tag{5}$$

where $A = \sum_{i=1}^{n} 1 \Big/ \left(4a_i \beta_{ECD}{}^2\right)$

$$B = \sum_{i=1}^{n} \alpha_{ECD} \Big/ \left(2a_i \beta_{ECD}{}^2\right) \quad \text{and}$$

$$C = \sum_{i=1}^{n} \left[(1/4a_i)\left(\alpha_{ECD}{}^2/\beta_{ECD}{}^2 - b_i^2\right) + c_i\right] \tag{6}$$

are the equivalent fuel cost coefficients expressed in terms of the cost functions of the individual plants. In Economic Dispatch the power demand, which is specified by the dispatcher, is the known quantity and the target is to minimize the total operating cost (fuel cost) involved in generating equivalent power to meet the specified demand. Whereas, in the case of Fuel Target Dispatch the total fuel cost is the specified quantity, and the target for optimization is to maximize the total generation (i.e. total demand in the loss neglected case). The higher the amount of generation for the given operating cost, the higher will be the benefit.

Emission Target Dispatch module

The Emission Target Dispatch is similar to the Fuel Target Dispatch except that it deals with emission coefficients. If the total emission, E_t, is specified as the hourly emission target, which has to be met by a utility in order to meet the environmental standards, then the corresponding system demand, P_D, that has to be shared by all the thermal plants operating in parallel, can be derived in line with the Fuel Target Dispatch as

$$P_D = \left\{-E + \left[E^2 - 4D(F - E_t)\right]^{1/2}\right\} \Big/ (2D) \quad \text{MW} \tag{7}$$

where D, E, and F are the equivalent emission coefficients expressed in terms of the emission coefficients of the individual plants. If the power system generates power more than the determined value of P_D, then the environmental constraints will be violated and the utility has to pay the environmental penalty. The solution algorithm presented herewith is designed such that it is capable of dealing with different types of fuels and emissions.

Training through example

The following section provides basic training with a six-generating-plant power system.[8] The first thing to be done is to complete the System Information. In this example, the System Name is CPC TPS and the Date of Commissioning of the power system is November 19, 1993. The Number of Plants in operation is six and the Power Demand at a particular time is considered as 1500 MW. The Type of Fuel used is coal and it is selected from the Fuel Type pull-down list box. The information Emission Cost in $/kg is required only for performing Combined Economic and Emission Dispatch. The user can choose any training module first and then switch over to other modules.

Training on Economic Dispatch

A click on the Input Data menu opens a table for the data entry. The table in this case has six rows, which corresponds to the number of plants, and the number of columns is always fixed as six, which equals the sum of the number of fuel cost and number of emission coefficients. The user is supposed to enter numeric data; a validation of the data entry is done, and if the user tries to enter a non-numeric value, a dialog box appears instructing the user to enter numeric data only. This package deals with different types of thermal power plant emissions like nitrogen oxides, sulphur dioxide, and carbon dioxide. Nitrogen oxide is chosen as the power plant emission and the corresponding emission coefficients are entered. Figure 2 shows the complete data entry for the six-generator system. Once the data has been entered, the Economic Dispatch module is chosen from the Dispatch Options component. Then, among the three Plant wise Options, the Individual Plant Generation has been selected first. A click on the Calculate menu performs the calculations and displays the Individual Plant Generations on the Graphical Display Screen, in 2D bar chart form as shown in Fig. 3. Depending on the choice, the screen displays the plants' contributions in other forms like 3D bar, 2D area, 2D step, 2D line, and 2D pie charts. Since the screen is of an adjustable nature, it is adjusted for better appearance of the output and the chart title is placed at the top of the chart for convenience.

Data Input

	Fuel Cost Coefficients			Emission Coefficients		
	a	b	c	d	e	f
Plant 1	0.15247	38.53973	756.80	0.00419	0.32767	13.86
Plant 2	0.10587	46.15916	451.33	0.00419	0.32767	13.86
Plant 3	0.02803	40.39655	1049.99	0.00683	-0.54551	40.27
Plant 4	0.03546	38.30553	1243.53	0.00683	-0.54551	40.27
Plant 5	0.02111	36.32782	1658.57	0.00461	-0.51116	42.90
Plant 6	0.01799	38.27041	1356.66	0.00461	-0.51116	42.90

Fig. 2 *Input data for the six plants.*

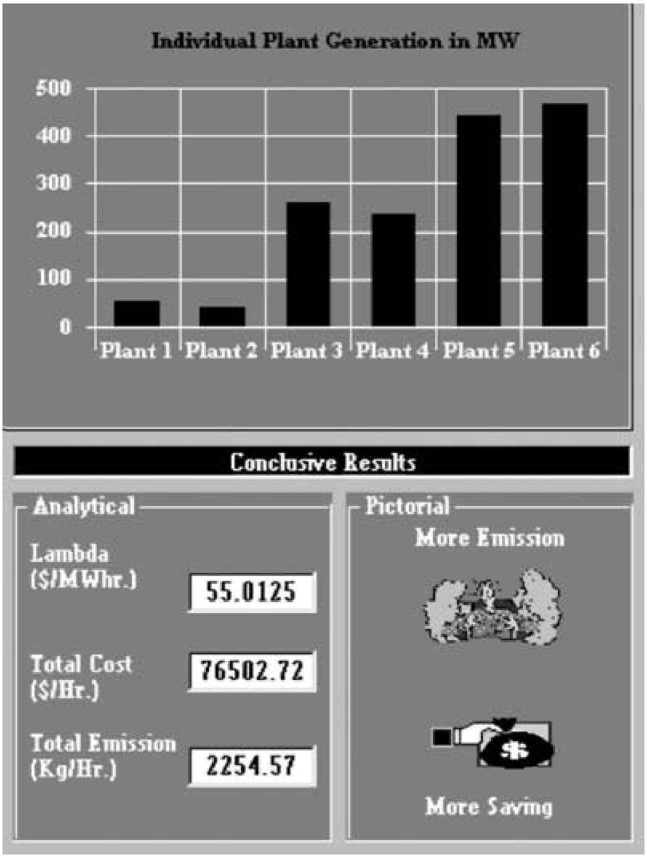

Fig. 3 *Economic dispatch results.*

The user can also view the Individual Plant Fuel Cost and the Individual Plant Emission on the Graphical Display Screen one at a time, just by clicking the Calculate menu. Apart from the individual plant contributions display in Fig. 3, the overall key results, namely the incremental cost of received power (λ in \$/MW h), total operating cost (\$/h), and the corresponding total emission (kg/h) are shown precisely under the Conclusive Results – Analytical heading. Also a symbolic representation of the level of saving in cost and the total emission are shown under the Conclusive Results – Pictorial heading. It could be seen that, whatever the Plantwise Option chosen, the conclusive results remain the same. The user can try with different fuels, emissions, and power demand conditions. Print preview of the system information, input data, display of individual plant contributions, key results etc can be had through the Print Preview menu and this information can be printed directly from there itself.

Training on emission dispatch

With the same input data, and the same system information, the Emission Dispatch module is chosen from the Dispatch Options component and the user can choose any one of the three Plantwise Options. A click on the Calculate menu performs the calculations and displays the individual plant contributions as chosen by the user, on the Graphical Display Screen. The user can try with all six Graphical Options. Figure 4 shows the typical output of the Emission Dispatch option with 2D pie graphical display of the Individual Plant Emission on the Graphical Display Screen. The user can try with different fuels, emissions, and power demand conditions and also with the remaining Individual Plantwise Options.

Training on Combined Economic and Emission Dispatch

In order to perform the Combined Economic and Emission Dispatch, the Emission Cost in $/kg should be entered in the System Information component box. A message box instructs the user if he/she fails to do so. Figure 5 shows the typical output of

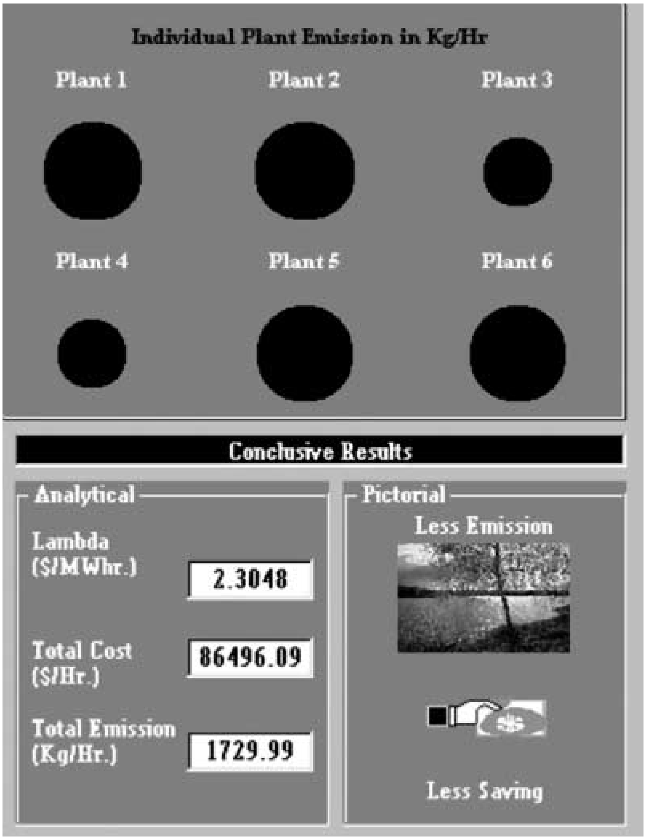

Fig. 4 *Emission dispatch results.*

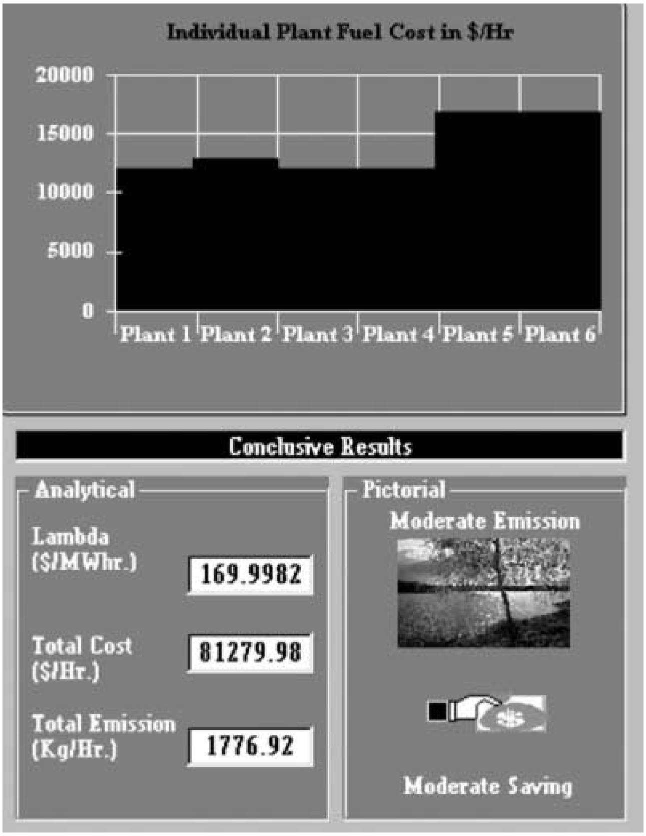

Fig. 5 *Combined economic and emission results.*

the Individual Plant Fuel Costs in 2D step graphical display for an Emission Cost of 45 $/kg.

The user can further try with different values of the Emission Cost in $/kg. A comparison of the key results of the three Dispatch Options reveals that: Economic Dispatch offers the minimum total operating cost at an enhanced emission level, whereas Emission Dispatch offers the minimum emission at an enhanced total operating cost, but the Combined Economic and Emission Dispatch offers the moderate value of the total operating cost (i.e. the cost lies in between the costs of economic and emission dispatches) and an emission level in between the emissions of the economic and emission dispatches.

Training on Fuel Target Dispatch

In the case of Fuel Target Dispatch, the user specifies the total fuel cost (operating cost). Keeping the same input data, the user can select the Fuel Target Dispatch module from the Dispatch Options component. As soon as the user selects, a message box appears instructing the user to enter the target fuel cost. In this case, the fuel target cost is selected as 85 000 $/h. As before, the user can select any Plantwise Options, and Graphical Display Options and then can proceed with the Calculate menu. Figure 6 shows the expected power generation (power demand in this case) for the specified fuel target cost. The maximum power that could be generated by the system with the target cost provided is 1652.16 MW. In other words, the maximum demand that could be met by the six generators without considering transmission loss is 1652.16 MW. Any attempt at excess power generation or any plan of meeting excess demand greater than the computed value of 1652.16 MW will result in a higher fuel cost budget.

Figure 7 shows the conclusive results of the fuel target dispatch. It may be noticed that, though the user has fixed the Total Fuel Target Cost as 85 000 $/h, the actual

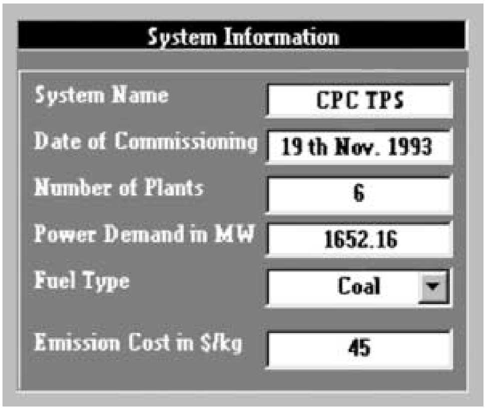

Fig. 6 *Power generation from fuel target dispatch.*

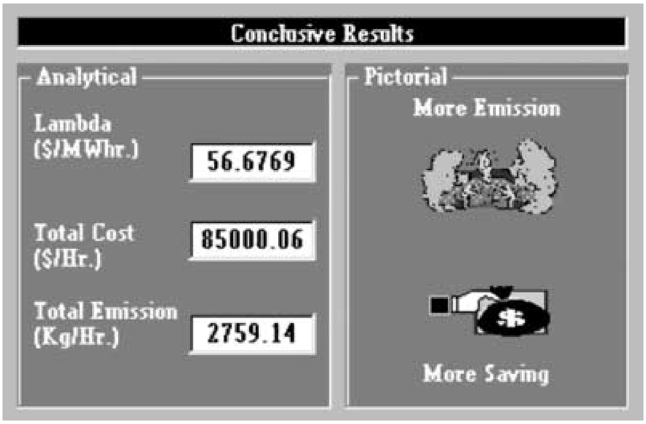

Fig. 7 *Conclusive results of fuel target dispatch.*

cost is found to be 85 000.06 \$/h. Such a small difference of 0.06 \$/h in fuel cost is due to the two-decimal-place approximation introduced in the programming part of the expected power generation computation. The nitrogen oxide emission for the given fuel target is found to be 2759.14 kg/h. The fuel target cost dispatch algorithm is designed such that it maximizes the power generation without any due consideration to emission control and hence the emissions in this case will be higher. This type of dispatch is very useful for independent power producers who plan for budget constrained power generation. The user can try with different fuel cost targets, with different fuel types and also with different types of emissions.

Training on emission target dispatch

Power producers have to meet the environmental criteria set by the Environmental Protection Agency. Emission target dispatch is one way of achieving this goal. In this dispatch, the user has to specify the total emission which has to be maintained. Keeping the same input data, the user can select the Emission Target Dispatch module from the Dispatch Options component. As soon as the user selects, a message box appears asking the user to enter the emission target. In this case, the nitrogen oxide emission target is selected as 2000 kg/h. As before the user can select any Plantwise Options, and Graphical Display Options and then can proceed with the Calculate menu. Figure 8 shows the expected power generation for the specified emission target. The dispatch output indicates that the six-generator system could generate or meet a maximum power of 1612.58 MW without violating the stated emission target. The conclusive results of the emission target dispatch are shown in Fig. 9. Due to the two-decimal-place approximations introduced in the power demand calculations, sometimes the calculated value of the emission target may not be exactly equal to the specified emission target. The emission target dispatch algorithm is designed such that it maintains the emission at the target value by controlling the generation level without making any attempt to reduce the operating cost

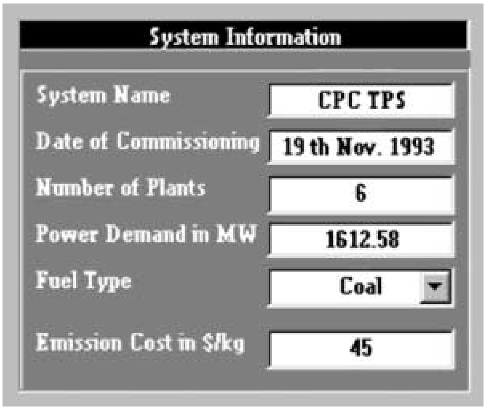

Fig. 8 *Power generation from emission target dispatch.*

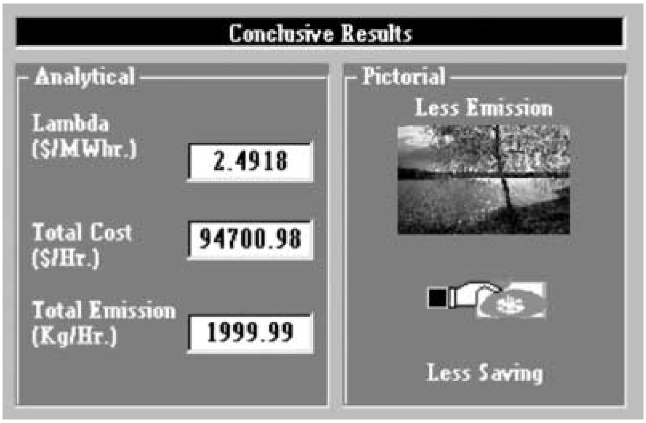

Fig. 9 *Conclusive results of emission target dispatch.*

and hence the operating cost in this case is found to be 94 700.98 $/h, which is very high. The user can try with different emission targets, different types of emissions, and also with different fuels.

Conclusion

This paper has presented five modules for providing basic training for power system engineering students, on the economic operation of power systems with environmental constraints, with the help of a computer package developed by the authors. The students, and colleagues of the authors, and also some non-technical personnel involved in the power business, identify the package as an elegant basic training kit for power engineering students, and also for experienced system engineers without much computing background. However, this package has some data storage and data manipulation limitations. In a future version of the package, integration of the database management system will be introduced.

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