Task Force on Modern Heuristic Optimization Test Beds
Working Group on Modern Heuristic Optimization
Intelligent Systems Subcommittee
Power System Analysis, Computing, and Economic Committee

Competition

on

Application of Modern Heuristic Optimization Algorithms for Solving Optimal Power Flow Problems

Problem Definitions and Implementation Guidelines

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1. AIM OF THE COMPETITION

Like in other engineering fields, the application of heuristic optimization algorithms to solve power system optimization problems is receiving great attention due to their potential to deal with inherent mathematical complexities such as high-dimensionality, non-linearity, non-convexity, multimodality and discontinuity of the search space. Moreover, the experience gained in the development and use of different types of heuristic optimization concepts motivates further research effort to devise novel mechanisms for improved search exploration and exploitation.

One of the targets of the Working Group on Modern Heuristic Optimization under the IEEE PES Power System Analysis, Computing, and Economics Committee is to develop power system optimization test beds where the general applicability and effectiveness of emerging tools in the field of heuristic optimization can be evaluated and compared with one another. Thus, as an initial step, it has been decided to organize a special panel at the 2014 IEEE PES General Meeting, which will be preceded by a competition focusing on application of these tools for solving optimal power flow (OPF) problems held.

The competition aims at performing a comparative assessment of the search capability of different heuristic optimization algorithms. The assessment will base on statistical tests performed on results submitted by interested participants. For this purpose, an encrypted file has been prepared based on functionalities of Matlab and MATPOWER toolbox in order to perform automatic evaluation of OPF's objective function and constraints as well as to collect and store automatically the results. In this way, the OPF problems are treated as black box tasks, which should be solved for different test cases based on four selected test networks. Preliminary tests have proven that all optimization test cases are solvable, but some of them constitute very hard-to-solve tasks, in which finding feasible solutions is a key challenge. Therefore, the participants are requested to focus exclusively on implementation of the particular heuristic optimization algorithm to be used, which could include any special strategy for constraint handling or treatment of discrete/binary optimization variables associated to transformer and compensation devices.

The encrypted file named *test_bed_OPF.p* along with other exemplary Matlab m-files, which are intended for easy adaptation to any heuristic optimization algorithm, are included in the zipped folder named *test_bed_OPF_V13.zip*. This folder also provides complete details (in MATPOWER format) and updated diagrams (in Microsoft Visio format) of each test system in the subfolders named *input_data*, and *Docs*, respectively. Please read carefully the instructions given in every m-file and in *readme.txt* file, which provide precise indications about Matlab based procedural and implementation aspects.

Final results, which are automatically saved for each optimization test case over 31 independent optimization trials in formatted ASCII-files contained in a zipped folder named *output_data_implementation_name.zip*, are needed for statistical tests to be performed in the competition, so this folder should be sent to istvan.erlich@uni-due.de until 20th March 2014 in accordance with the guidelines provided in this technical report. The implementation codes of each algorithm entering the competition must also be submitted along with final results for full consideration in the evaluation. The submitted codes will be used for further tests, which are intended to crosscheck the submitted results. The submitted codes will be in the public domain and no intellectual property claims should be made.

2. DEFINITION OF OPF PROBLEMS

2.1. Overview

Well known formulations of optimal reactive power dispatch (ORPD) and optimal active-reactive power dispatch (OARPD) problems, i.e. [1]-[2], are implemented in *test_bed_OPF.p*, such that different OPF test cases can be performed for four selected test systems with different sizes and structural complexities.

test_bed_OPF.p has been developed for calculation of objective function and constraints of all OPF tasks as well as for automatic collection and storage of results in formatted ASCII-files. It uses the functions for modeling and load flow calculation available in MATPOWER toolbox [3], which can be freely downloaded from http://www.pserc.cornell.edu/matpower/. The zipped folder *test_bed_OPF_V13.zip* contains this code along with instructions on how to use it as well as an implementation example with basic particle swarm optimization (PSO) algorithm. The code is considered as a black box, so it cannot be modified by participants.

Each participant is encouraged to work exclusively on the particular optimization algorithm to be used. The use of any type of constraint handling technique is allowed. An exemplary routine for constraint handling is provided in the file *constraint_handling.m*. This routine does not affect the calculations done in *test_bed_OPF.p*, which calculates internally the fitness $f^{'}$ by using (1).

$$f^{'} = f + \rho \sum_{i=1}^{n} \max\left[0, g_i\right]^2 \qquad (0)$$

where ρ is a penalty factor that is set to a high value, i.e. 1E+7, for both ORPD and OARPD problems.

It is clarified that the fitness calculation performed by *test_bed_OPF.p* is exclusively intended for ascertaining fulfillment of constraints in the competition. The values of $f^{'}$ are automatically recorded at a predefined rate of 100 function evaluations, i.e. power flow calculations, and stored in an formatted ASCII-file, which will be used later in algorithms' performance evaluation.

The *rounding.m* file is an exemplary external function that can be employed for rounding the real numbers used to code discrete/binary optimization variables. You are allowed to modify this file to include your own rounding strategy, but the function syntax, i.e.

x_out=rounding(x_in), should be kept, because it is called internally in *test_bed_OPF.p* before every function evaluation. x_in denotes one individual component of the sequence of discrete/binary variables from the vector of optimization variables to be generated using the offspring creation scheme of your optimization algorithm. Please read the instructions given in *main_commented.m* to determine the indexes (elements) of the vector of optimization variables defined as discrete/binary variables. *test_bed_OPF.p* is configured to automatically round the values corresponding to the discrete/binary coded variables to the nearest integer, so this rounding approach will be internally used regardless of whether your algorithm uses a rounding strategy or not. If a rounded variable violates its boundary, it will be automatically fixed in *test_bed_OPF.p* to the corresponding limit. Please also refer to *main_commented.m* file to gather how to obtain all power system and optimization related information, e.g. location of controllable transformer and compensation devices, problem dimensionality, bounds of optimization variables, steps of discrete variables.

Slightly modified versions of IEEE 57- 118- and 300-bus test systems are used to evaluate ORPD and OARPD problems. Based on details given in [4] for system buses and branches, the data of each system has been structured in MATPOWER data format. Branch thermal limits were defined based on reference values given in [5]. Also, the ORPD problem should be evaluated by using a test offshore wind power plant (WPP), which is based on the typical layout given in [6]. A comparative summary of the characteristics of all test systems is shown in Table 1, whereas description of the optimization test cases to be performed for each system is given in the following subsections.

Table 1: Composition of test systems

Item/System		**Offshore WPP**	**IEEE 57 bus system**	**IEEE 118 bus system**	**IEEE 300 bus system**
Generators		18	7	54	69
Loads		1	42	99	201
Lines/cables		20	63	177	304
Transformers	Stepwise	2	15	9	62
	Fixed tap	18	2	0	45
Shunt compensation	Binary on/off	0	3	14	14
	Stepwise	1	0	0	0
	Continuous	1	0	0	0

2.2. IEEE 57 bus system

2.2.1. ORPD test case

- **Target:** Minimize the total active power transmission losses while fulfilling constraints (associated to nodal balance of power, nodal voltages, allowable branch power flows, and generator reactive power capability) for normal (non-contingency) and selected N-1 conditions.
- **Constraints:** 178 for non-contingency conditions, and 177 for each N-1 condition.

- **Optimization variables:** 25, comprising 7 continuous variables associated to generator bus voltage set-points, 15 discrete variables associated to stepwise adjustable on-load transformer tap positions, and 3 binary variables associated to switchable shunt compensation devices.
- **Scenarios:** 1 - corresponding to a heavy loading condition.
- **Considered contingencies (N-1 conditions):** outage of branches 8 and 50.
- **Number of function evaluations:** 50000.

2.2.2. OARPD test case

- **Target:** Minimize the total fuel cost while fulfilling constraints (associated to nodal balance of power, nodal voltages, allowable branch power flows, generator reactive power capability, and maximum active power output of slack generator) for normal (non-contingency) and selected N-1 conditions.
- **Constraints:** 178 for non-contingency conditions, and 177 for each N-1 condition.
- **Optimization variables:** 31, comprising 13 continuous variables associated to generator active power outputs and generator bus voltage set-points, 15 discrete variables associated to stepwise adjustable on-load transformers' tap positions, and 3 binary variables associated to switchable shunt compensation devices.
- **Scenarios:** 1 - corresponding to a heavy loading condition.
- **Considered contingencies (N-1 conditions):** outages at branches 8 and 50.
- **Number of function evaluations:** 50000.

2.3. IEEE 118 bus system

2.3.1. ORPD test case

- **Target:** Minimize the total active power transmission losses while fulfilling constraints (associated to nodal balance of power, nodal voltages, allowable branch power flows, and generator reactive power capability) for normal (non-contingency) and selected N-1 conditions.
- **Constraints:** 492 for non-contingency conditions, and 491 for each N-1 condition.
- **Optimization variables:** 77, comprising 54 continuous variables associated to generator bus voltage set-points, 9 discrete variables associated to stepwise adjustable on-load transformer tap positions, and 14 binary variables associated to switchable shunt compensation devices.
- **Scenarios:** 1 - corresponding to a heavy loading condition.
- **Considered contingencies (N-1 conditions):** outages at branches 21, 50, 16, and 48.
- **Number of function evaluations:** 100000.

2.3.2. OARPD test case

- **Target:** Minimize the total fuel cost while fulfilling constraints (associated to nodal balance of power, nodal voltages, allowable branch power flows, generator reactive power capability, and maximum active power output of slack generator) for normal (non-contingency) and selected N-1 conditions.

- **Constraints:** 492 for non-contingency conditions, and 491 for each N-1 condition.
- **Optimization variables:** 130, comprising 107 continuous variables associated to generator active power outputs and generator bus voltage set-points, 9 discrete variables associated to stepwise adjustable on-load transformer tap positions, and 14 binary variables associated to switchable shunt compensation devices.
- **Scenarios:** 1 - corresponding to a heavy loading condition.
- **Considered contingencies (N-1 conditions):** outages at branches 21, 50, 16, and 48.
- **Number of function evaluations:** 100000.

2.4. IEEE 300 bus system

2.4.1. ORPD test case

- **Target:** Minimize the total active power transmission losses while fulfilling constraints (associated to nodal balance of power, nodal voltages, allowable branch power flows, and generator reactive power capability) for normal (non-contingency), and selected N-1 conditions.
- **Constraints:** 651 for non-contingency conditions, and 950 for each N-1 condition.
- **Optimization variables:** 145, comprising 69 continuous variables associated to generator bus voltage set-points, 62 discrete variables associated to stepwise adjustable on-load transformers' tap positions, and 14 binary variables associated to switchable shunt compensation devices.
- **Scenarios:** 1 - corresponding to a heavy loading condition.
- **Considered contingencies (N-1 conditions):** outages at branches 187, 176, and 213.
- **Number of function evaluations:** 300000.

2.4.2. OARPD test case

- **Target:** Minimize the total fuel cost while fulfilling constraints (associated to nodal balance of power, nodal voltages, allowable branch power flows, generator reactive power capability, and maximum active power output of slack generator) for normal (non-contingency) and selected N-1 conditions.
- **Constraints:** 651 for non-contingency conditions, and 950 for each N-1 condition.
- **Optimization variables:** 213, 137 continuous variables associated to generator active power outputs and generator bus voltage set-points, 62 discrete variables associated to stepwise adjustable on-load transformers' tap positions, and 14 binary variables associated to switchable shunt compensation devices.
- **Scenarios:** 1 - corresponding to a heavy loading condition.
- **Considered contingencies (N-1 conditions):** outages at branches 187, 176, and 213.
- **Number of function evaluations:** 300000.

2.5. Offshore wind power plant (WPP)

The layout of the WPP system is depicted in Fig. 1. It corresponds to a commonly used topology for offshore WPPs, which is connected to the main grid using an AC cable with transformers at both ends. Due to large charging currents of AC cables, line reactor X_{sh2} on offshore side is permanently connected to the cable. Reactor X_{sh1} can be adjusted in a continuous manner to provide Var control on the onshore end of the cables. The stepwise regulated capacitor C_1 is intended for auxiliary reactive power support. L_1 represents a dummy load whose real part corresponds with WPP's currently generated active power and the imaginary component with the reactive power requirement at the point of the common coupling – PCC – (q_{ref}), which is related to the rating of the WPP independently of the injected active power at PCC. The difference between the injection from the WPP and the fictitious consumption associated to L_1 quantifies the total losses of the wind energy system and fulfillment of the reactive power requirement at PCC.

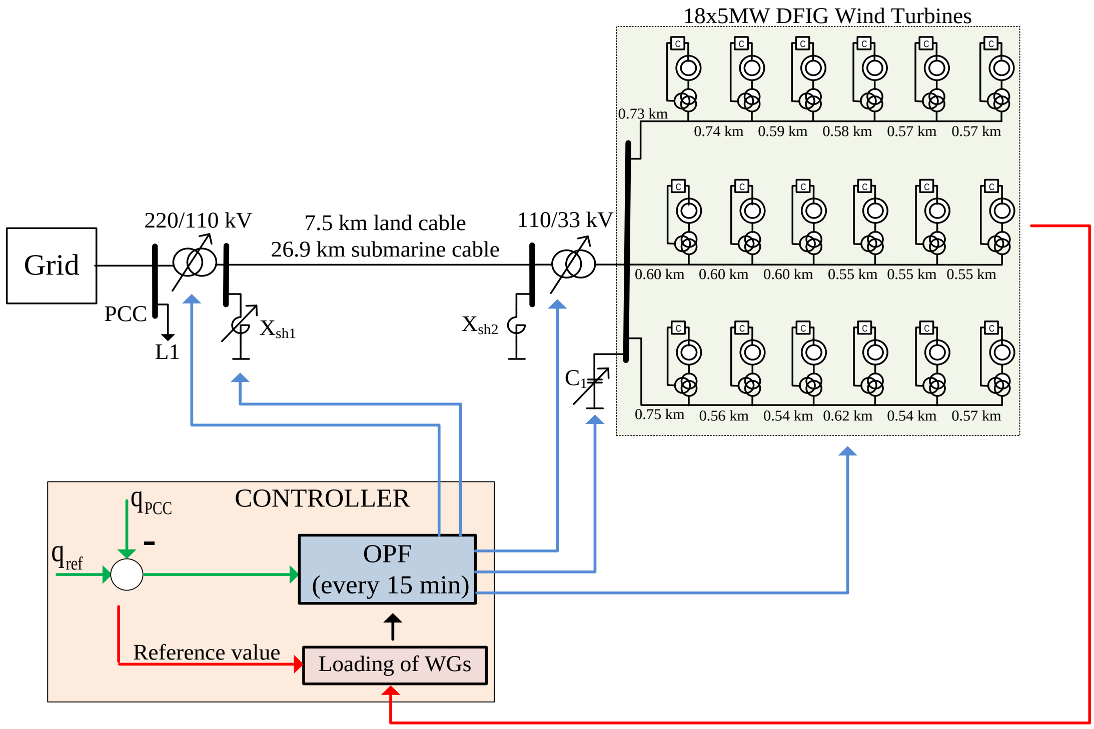

Fig. 1. Offshore WPP with optimization based management of reactive power sources

Assuming the availability of a data acquisition system to provide measurements related to the actual status of all wind generators, transformers, and compensation devices within the WPP, a control strategy is defined to continuously fulfill q_{ref} through optimum management of the available WPP's Var sources during normal (i.e. steady-state or quasi steady-state) conditions [6]. To highlight the relevance of online optimal reactive power control problem, the reactive power requirements corresponding to the actual operating condition are defined as stepwise changes of q_{ref} throughout 24 hours as shown in Fig. 2. The figure also illustrates the independent variability of WPP output power. Each point of these curves defines a scenario, for which the ORPD problem should be solved. Considering 15 min intervals, it results in 96 scenarios, some of them entailing hard-to-solve optimization tasks. In the file *main.m*, it is possible to select any of the scenarios for individual testing.

2.5.1. ORPD test case

- **Target:** Minimize the total active power transmission losses while fulfilling constraints (associated to nodal balance of power, nodal voltages, allowable branch power flows, and difference between q_{ref} and q_{PCC}) for normal conditions. q_{PCC} is the actual reactive power injection at the PCC.
- **Constraints:** 123.
- **Optimization variables:** 22, comprising 18 continuous variables associated to wind generator reactive power set-points, 2 discrete variables associated to stepwise adjustable on-load transformers' tap positions, a discrete variable defining the stepwise adjustment of C_1, and a continuous variable defining the adjustment of X_{sh1}.
- **Scenarios:** 96 - corresponding to all 15 min interval points of the curves shown in Fig. 2.
- **Number of function evaluations:** 10000.

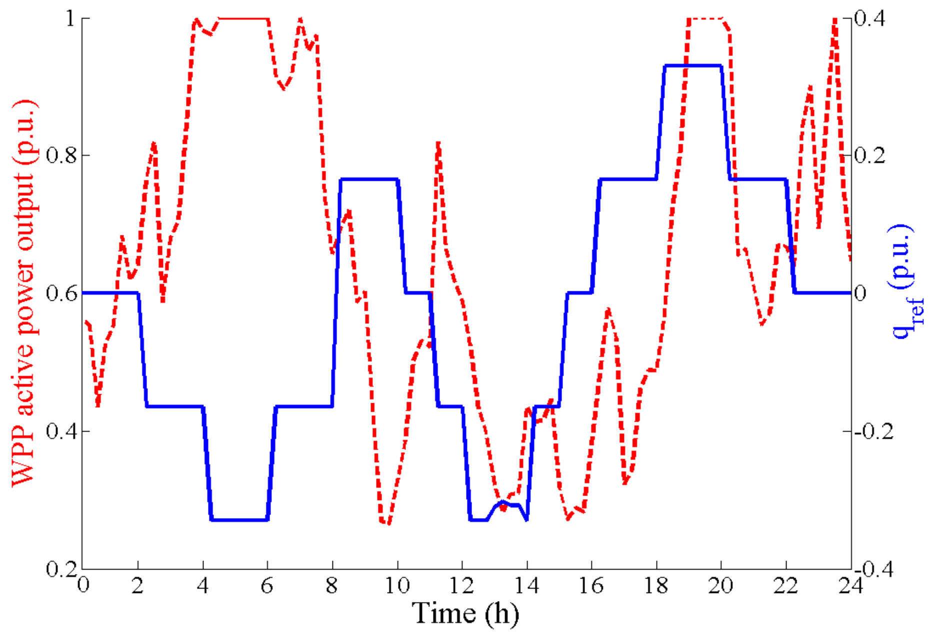

Fig. 2. Exemplary q_{ref} and WPP output power profile

3. IMPLEMENTATION ASPECTS

The *main.m* file contained in *test_bed_OPF_V13.zip* allows selecting the OPF test case and scenario to be solved, as well as calling the implementation routine written for your optimization algorithm, and deciding whether or not to employ shared-memory parallel computing functionality of Matlab's Parallel Computing Toolbox. The file *main_commented.m* provides a thorough description of the overall procedure and adaptation of the provided files for your implementation.

3.1. Experimental setting

- **Trials/problem:** It is fixed to 31 in *test_bed_OPF.p* by using field *proc.n_run*, which is declared global. For initial testing purposes, you are allowed to change the value of this variable to a lower one (see lines 542-549 in *main_commented.m*) but please remember that 31 trials are mandatory for performance evaluation in the competition.

- **Stop criterion:** *test_bed_OPF.p* is configured to terminate automatically an optimization trial upon completion of the maximum number of function evaluations. Lines 111-128 of *psopt.m* provide an example on how to prematurely stop running a current trial in your implemented algorithm. Nevertheless, it is pointed out that automatic storage of intermediate results in formatted ASCII files will not be performed in this case, so you may have to add some commands to your implementation for recording the progress of objective function, fitness, constraint fulfillment, and optimization variables. Please remember that the maximum number of function evaluations established in the previous section is mandatory for performance evaluation in the competition, and only the ASCII files created automatically by *test_bed_OPF.p* should be submitted for evaluation.
- **Initialization:** uniform random initialization within the search space.
- **Encoding:** If the algorithm requires encoding, then the encoding scheme should be independent of the specific optimization tasks and governed by generic factors such as search ranges, dimensionality of the problems, etc.
- **Algorithm tuning:** The participants are allowed to tune their algorithms. Details of tuning procedure, corresponding dynamic ranges of algorithm's parameters, and final parameter values used should be provided to the organizers and thoroughly discussed in the panel as well.

3.2. Results to be submitted

test_bed_OPF.p performs automatic saving of results in formatted ASCII-files contained in a zipped folder named *output_data_implementation_name.zip*. The folder is created once a scenario of a test case for an individual system is solved for first time. Newly created results are automatically added to this folder. Before submission of results, please check whether the folder contains a total of 510 files (corresponding to 5 files associated to ORPD and OARPD for the three IEEE test systems and ORPD for the 96 scenarios of the WPP). Each of the 5 associated files should automatically be assigned names according to the following convention:

(Name of your implementation)_(Number of buses denoting the system)_(Number of test case)_(Number of scenario)_(xyz).txt

where (xyz) stands for different items to be stored:

- objective: recorded objective function convergence data for each optimization trial. The convergence data is recorded after the first and after every 100 function evaluations.
- fitness: recorded fitness convergence data for each optimization trial. The convergence data is recorded after the first and after every 100 function evaluations.
- variables: final best solution achieved by the optimization algorithm in each optimization trial

- constraint_violation: constraint violation vector corresponding to final best solution in each optimization trial
- complexity: computing time associated to each optimization trial

The file *output_data_implementation_name.zip* together with the implementation codes of the algorithm being used should be summited to istvan.erlich@uni-due.de by 20th March 2014. Details on the computing system and the programming language used should also be provided. It is discouraged to attempt deliberate manipulation of the ASCII-files, e.g. replacement of the files corresponding to a given optimization test case by new ones collecting the results of the best 31 trials picked up after performing a myriad of optimization trials.

3.3. Evaluation criteria

Although the submitted results will be mainly assessed in terms of the achieved final fitness values, which are automatically saved in ASCII-files by the *test_bed_OPF.p* file, the fulfillment of the established bounds for the optimization variables will be also considered. Based on these results, a ranking index will be established, which accounts for different problem complexities.

4. REFERENCES

[1]. Saraswat, and A. Saini, “Optimal reactive power dispatch by an improved real coded genetic algorithm with PCA mutation,” 2nd International Conference on Sustainable Energy and Intelligent Systems, pp. 310-315, July 2011.

[2]. C.-M. Huang, S.-J. Chen, Y.-C. Huang, and H.-T. Yang, "Comparative study of evolutionary computation methods for active-reactive power dispatch," IET Generation, Transmission & Distribution, vol.6, no.7, pp. 636- 645, July 2012.

[3]. R. D. Zimmerman, C. E. Murillo-Sánchez, and R. J. Thomas, "MATPOWER: Steady-State Operations, Planning and Analysis Tools for Power Systems Research and Education," IEEE Transactions on Power Systems, vol. 26, no. 1, pp. 12-19, Feb. 2011.

[4]. http://www.ee.washington.edu/research/pstca/. Last accessed on August 15, 2013.

[5]. Y.H. Song, and X.F. Wang, Operation of Market-Oriented Power Systems. Springer Verlag: London, pp. 146, 2003. ISBN 978-1-85233-670-7.

[6]. V. H. Pham, J.L. Rueda, and I. Erlich, “Online optimal control of reactive sources in wind power plants”, IEEE Transactions on Sustainable Energy- Special Issue on Real-Time Applications of Intelligent Methods in Sustainable Power and Energy Systems. [Online] Available at http://ieeexplore.ieee.org.