Remote Blackstart of Steam Electric Station Using Modified Barrier-Augmented Lagrangian Method

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Abstract: The remote blackstart operation is a significant industry problem because a considerable portion of the electricity is supplied by base-loaded steam electric units. These units are located remote from the load centers supplying power over high-and extra-high voltage lines, they generally have no blackstart capability and need considerable off-site power for startup operations. On the other-hand, combustion turbine units are installed close to the load centers, they are used as cycling units to meet the daily peak demands, and need no off-site power for startups. Although they have not been designed, nor intended as the blackstart source, they can be an economical and a very attractive option for the remote blackstart of steam electric units, provided they meet the reactive power requirements.

This paper reports on application of a modified barrier-augmented Lagrangian (MBAL)-based nonlinear optimal power flow (OPF) method for maximizing reactive power capability of a twin combustion turbine for the blackstart of a remote steam electric unit. The feasibility of the blackstart operation is demonstrated in the 12-Bus Test System that is in operation in a Mid-western utility.

Keywords: Remote Blackstart, Ancillary Service, Optimization, Reactive Power, Generator Excitation

1. INTRODUCTION

The objective in this study was to address the remote blackstart problem, applying the Optimal Power Flow (OPF) based on the modified barrier-augmented Lagrangian (MBAL) method.

In the course of a blackstart operation, two limiting conditions place severe demands on the reactive power capability of the blackstart source. One extreme operating condition occurs during the initial energization of the transmission path when the combustion turbine station (CTS) is called upon to absorb the charging currents of the high- and extra-high voltage connecting lines. The other extreme operating condition, is when the combustion turbine generators supply the large amount of reactive power required during startup of the largest auxiliary motor in the steam electric station (SES). These under-and over-excitation demands can be met by optimum selections of the CTS step-up transformer and step-down auxiliary transformer tap positions, and by control of the generator voltage set points.

The blackstart operation is complicated by the fact that the generator step up and auxiliary transformers are typically equipped with no-load (fixed) taps. Therefore, in the planning phase and prior to the blackstart operation, the optimum tap positions for these transformers and the correct terminal voltage set point(s) for the generator need to be determined to satisfy the two conditions [1,2].

This paper describes blackstart of a coal-fired drum-type SES, from a remote CTS. The MBAL-based OPF is used to determine the feasibility of the blackstart, and to determine:

- The CTS generators over-and under-excitations required by the blackstart operation,
- The tap positions for the CTS generator step-up transformer and for the auxiliary step-down transformer to provide adequate lead and lag reactive powers, and
- The allowable voltages for the generator terminal at the CTS, and the allowable high and low voltage levels at the auxiliary bus in the SES.

The 12-Bus Test System being a typical blackstart system was obtained from a Midwestern utility for testing and verifying the MBAL-based OPF method and results.

The paper is organized as follows. Section 2 reviews linear and nonlinear optimization methods. Section 3 outlines the MBAL-based OPF method. Section 4 describes the 12-bus test system while Section 5 provides some simulation results of the MBAL-based OPF. The latter are checked against the Generator Reactive Capability (GRC) [3,4] and an interactive power flow programs in Section 6.

2 – STATE-OF-THE ART IN OPTIMIZATION

Since late 70s the work of Scott and Hobson [5] on Linear Programming (LP) has been widely used for power system optimization problems. Since mid 80s, the Interior Point Methods (IPMs) has become the most popular tool for solving constrained optimization problems with inequality constraints. The IPMs in general and the Primal-Dual IPMs in particular used for LP calculations have been a great success [13]. Not only the IPMs have become the mainstream in the modern optimization theory, but they also have been successfully applied to OPF problems [6]-[12]. The success of the IPM in LP stimulated applications of the basic Primal-Dual IPM ideas for NLP [16]. Although the Primal-Dual approach produced for a number of NLP problems reasonable results [16], still there is substantial gap in terms of numerical efficiency between LP and NLP calculations.

In LP calculations, it is possible to avoid ill-conditioning phenomena thanks to the special structure of the Log-barrier function Hessian coupled with substantial advances in numerical linear algebra [14]. In NLP, the structure of the corresponding Hessian is fundamentally different. It has an extra term that is the Hessian of the classical Lagrangian for the original problem (in LP calculations, the corresponding term is just the zero matrix). The extra term makes the ill conditioning in NLP fundamentally different from the corresponding effect in LP calculation. Therefore, there is a substantial gap between the efficiency of the IPM for LP and NLP calculations.

The OPF problems faced by the electric power industry are inherently nonlinear and of large dimension [15], [17]. Moreover, along with inequality constraints, they have nonlinear equations. To control the feasibility for the equations one has to introduce a penalty term. It can only increase the ill-conditioning effect. Therefore, in the following section we present an alternative to the classical barrier/penalty function approach for NLP. The approach is based on the Modified Barrier Function (MBF) [18] and Augmented Lagrangian (AL) [19] theories. It allows to eliminate the basic drawbacks of the classical barrier and penalty methods and at the same time to keep their best features.

3 - THE MBAL-BASED OPF METHOD

Maximizing the reactive power requirement of the 12-Bus Test System can be formulated as static Nonlinear Optimization (NLP) problems subject to both inequality and equality constraints. This is typically an Optimal Power Flow (OPF) problem where the equality constraints are the conventional power flow equations. The inequality constraints include the upper and lower bounds on the voltages across the system, the limitations on the generator reactive power capabilities, and the limits imposed on the apparent power flows through the transmission lines and transformers.

The Modified Barrier Function (MBF) [18] approach allows overcoming the difficulties of the classical Log-Barrier functions for inequality constraints whereas the Augmented Lagrangian (AL) [19] eliminates the basic problems associated with the penalty type functions for equality constraints. Before describing the MBAL method, the basic features that distinguish MBAL from the other approaches for large-scale NLP should be mentioned.

Let f, c_i and d_j be smooth enough functions. We consider the following problem:

$$x^* \in X^* = \\ Arg\min\{f(x)|c_i(x) \geq 0, i = 1,\ldots,p; \\ d_j(x) = 0, j = 1,\ldots,q\}. \tag{1}$$

We apply the MBF methodology [18] for inequality constraints and the Augmented Lagrangian for the equations [19]. The MBAL function $\mathsf{L} : \Re^n \times \Re_+^p \times \Re^q \times \Re_+ \rightarrow \Re$, was introduced in [20], as follows:

$$\mathsf{L}(x, l, v, k) = f(x) - k^{-1}\sum_{i=1}^{p} l_i \ln(kc_i(x)+1) - \\ \sum_{i=1}^{q} v_i d_i(x) + 0.5k\sum_{i=1}^{q} d_i^2(x) \tag{2}$$

The first two terms represent the Lagrangian function for the equivalent problems in the absence of the equality constraints, because for any fixed $k > 0$, the system $\ln(kc_i(x)+1) \geq 0, i = 1,\ldots,p$ is equivalent to $c_i(x) \geq 0, i = 1,\ldots,p$. The last two terms represent the Augmented Lagrangian for equality constraints [19]. Along with the classical Lagrangian term, $-\sum_{i=1}^{q} v_i d_i(x)$, there is a penalty term, $0.5k\sum_{i=1}^{q} d_i^2(x)$, which is designed to penalize the violation of the equality constraints. Keeping in mind that the MBF function given by

$$F(x, l, k) = f(x) - k^{-1}\sum_{i=1}^{p} l_i \ln(kc_i(x)+1) \tag{3}$$

has all the characteristics of the Interior Augmented Lagrangian (see [18]), one can view the MBAL $\mathsf{L}(x, l, v, k)$ as Interior-Exterior Augmented Lagrangian.

Before describing the MBAL-multipliers method, a few important characteristics of the MBAL function at the primal-dual solution should be emphasized. In contrast to the Classical Barrier Function, the MBF exists at the solution together with its derivatives of any order. Moreover for any $k > 0$, the MBAL possesses the following important properties at the primal-dual solution:

1^0. $\mathsf{L}(x^*, l^*, v^*, k) = f(x^*).$ (4)

2^0. $\nabla_x \mathsf{L}(x^*, l^*, v^*, k) = \nabla_x L(x^*, l^*, v^*) = 0$, (5)

where $L(x, l, v) = f(x) - \sum_{i=1}^{p} l_i c_i(x) - \sum_{i=1}^{q} v_i d_i(x)$

is the Classical Lagrangian for the original problem (1).

3^0.
$$\nabla_{xx}^2 \mathsf{L}(x^*, l^*, v^*, k) = \nabla_{xx}^2 L(x^*, l^*, v^*) + \\ k\nabla c^T(x^*)\Lambda^*\nabla c(x^*) + k\nabla d^T(x^*)\nabla d(x^*) \tag{6}$$

where

$$\nabla c(x) = J(c(x)) \text{ and } \nabla d(x) = J(d(x))$$

are the Jacobians of $c(x)$ and $d(x)$. Consequently, the MBAL not only exists at the primal-dual solution together with its derivatives of any order, but for $l = l^*$ and $v = v^*$, it is also the exact smooth approximation of a nonsmooth function, minimum of which coincides with x^*. In addition, under the standard second order optimality conditions for (1), the MBAL Hessian $\nabla^2_{xx} L(x^*, l^*, v^*, k)$ is positive definite due to the Debreu theorem (see, e.g., [18]) independently from the convexity of f, c_i, d_j for any $k \ge k_0 > 0$ if k_0 is large enough. Therefore, for any pair (l, v) close enough to (l^*, v^*), the MBAL $L(x, l, v, k)$ is strongly convex in x regardless upon whether the objective function and the constraints are convex or not. Considering the smoothness of $L(x, l, v, k)$ in $x \in \Re^n$, one can expect Newton's method for primal minimization MBAL to be efficient. It is interesting to note that the MBAL method generates the primal-dual sequence $\{x^s, l^s, v^s\}$ while $k > 0$ can be fixed or be changed from step to step.

First, we describe the MBAL method under the fixed barrier-penalty parameter $k > 0$. For any $x^0 \in \Re^n$ one can find $k > 0$ such that $kc_i(x^0) + 1 > 0$. Therefore in contrast to the IPM, the numerical realization of the MBAL method does not require finding initial interior point. The initial dual approximation is not an issue either, so $l^0 = e \in \Re^p$ and $v^0 \in \Re^q$ can be taken as an initial approximation for dual vectors. It is assumed that $\ln t = -\infty$, $t \le 0$. Let the approximation (x^s, l^s, v^s) has been found already, the next approximation is calculated via

$$x^{s+1} = \arg\min\{L(x, l^s, v^s, k) \,|\, x \in \Re^n\} \tag{7}$$

i.e. $$x^{s+1} : \nabla_x L(x^{s+1}, l^s, v^s, k) = 0 \tag{8}$$

The new Lagrange multipliers are given by

$$l_i^{s+1} = l_i^s (kc_i(x^{s+1}) + 1)^{-1},\ i = 1, \dots, p \tag{9}$$

$$v_j^{s+1} = v_j^s - kd_j(x^{s+1}),\ j = 1, \dots, q \tag{10}$$

Therefore from (8), (9) and (10) we have

$$\nabla L(x^{s+1}, l^s, v^s, k) = \nabla f(x^{s+1}) - \sum_{i=1}^{p} l_i^{s+1} \nabla c_i(x^{s+1}) - \sum_{j=1}^{q} l_j^{s+1} \nabla d_j(x^{s+1}) = \nabla_x L(x^{s+1}, l^{s+1}, v^{s+1}) = 0 \tag{11}$$

In other words, the Lagrange multipliers associated with inequality constraints are updated as in the MBF method [18] while the Lagrange multipliers associated with the equality constraints are updated as in the Augmented Lagrangian methods [19]. The convergence of the MBAL method is due to the update of the Lagrange multipliers while $k > 0$ is fixed so that the condition number of the MBAL Hessian remains stable and the convergence domain of Newton's method for the primal minimization does not shrink to a point. One can expect that the domain where Newton's method is "well defined" will remain large enough up to the end of the computational process. It makes the computation process robust and, eventually, produces very accurate results. The MBAL is an exterior point method in primal space because x^s usually does not satisfy neither the primal inequality nor the equations.

It was proven in [20] that both the primal sequence $\{x^s\}$ and the dual sequence $\{y^s\} = \{l^s, v^s\}$ converge to the primal-dual solution under the standard second-order optimality conditions. Moreover, the rates of convergence is Q-linear, i.e. for the primal $\{x^s\}$ and the dual $\{y^s\} = \{l^s, v^s\}$ sequences, which were generated by formulas (3)-(6), the following estimation takes place:

$$\|x^{s+1} - x^*\| \le \frac{c}{k}\|y^s - y^*\|,\ \|y^{s+1} - y^*\| \le \frac{c}{k}\|y^s - y^*\| \tag{12}$$

where, $c > 0$ is independent of $k \ge k_0 > 0$ and $k_0 > 0$ is large enough.

It is important to emphasize that although the primal optimization is taking place in the enlarged feasible set, the asymptotic feasibility is guaranteed due to the formulas (9)-(10) for the Lagrange multipliers update when the penalty barrier parameter $k > 0$ is fixed. Moreover, under the standard second order optimality condition, we have the estimation (12). It also follows from (12) that it is possible to get up to Q-superlinear rate of conversion if we increase $k > 0$ from step to step. Generally speaking, the bigger is $k > 0$, the better it is for the conversion rate but at the same time, a very large k can make it difficult to find the primal minimizer.

The most time consuming operation in the MBAL method is to find an approximation for the primal minimizer. Finding the primal minimizer is, generally speaking, infinite procedure. Therefore, we used the stopping criteria [18] to find an approximation for the primal minimizer and use it in formulas (9), (10) for the Lagrange multipliers update.

To this end, various unconstrained minimization techniques can be applied. In the MBAL code, Newton's and BFGS methods were used [21]. In the first method, the penalty barrier parameter $k > 0$ is fixed while in the second method, $k > 0$ is increased from step to step. We would like to mention that the convergence of the MBAL method is not due to the unbounded increase of the penalty barrier parameter $k > 0$ but rather due to the Lagrange multipliers update. Keeping in mind the flexibility of the MBAL method in terms of the value of the penalty barrier parameter $k > 0$, we change the parameter in the course of the computational process using the information obtained on the previous step.

The 12-Bus Test System and the 160-Bus Test System (not described in this paper) were tested with MBAL-based OPF method under both nonlinear inequality constraints and equations. The results obtained clearly indicate that the MBAL is a robust and efficient tool for solving OPF. In all problems that have been solved, the duality gap and the primal infeasibility were of the order 10^{-9}-10^{-11}. The number of Newton steps (NS) usually declines after each Lagrange multiplier update and from some point on "hot start", only one Newton step is required. Unlike for the Interior Point Methods (IPM), the numerical efforts per step for the MBAL are decreasing. Also, from step to step, it is possible to improve the accuracy with which one finds the unconstrained minimizer practically without extra computational efforts per step.

For MBAL method the dual "good" approximation is much more important than the primal approximation. If such approximation is not available then we use $l^0 = e \in \Re^p$ and arbitrary $v^0 \in \Re^q$ and find an approximation for the primal minimizer for $k>0$ large enough. A good approximation for the dual variable we obtain by formulas (9)-(10) using instead of x^{s+1} the primal approximation.

4 - TEST SYSTEM DESCRIPTION

The 12-Bus Test System used consists of the CTS as the blackstart source, the SES to be hot or cold restarted and the CTS-SES path [2].

The CTS consists of two pairs of generators feeding a common generator step up transformer (GSU Xfmr), with the following ratings: each pair of generators are rated at 42 MVA, 85 percent power factor and 13.8 kV; each GSU Xfmr is rated at 46 MVA, 14.4/118 kV, with reactance of 7.6% on 25 MVA base, equipped with six no-load taps between 95 and 107.5 percent; and the auxiliary transformer (AUX Xfmr) for each pair is rated at 300 kVA, 13.2/0.48 kV, with reactance of 1.99% on 300 kVA base, equipped with five no-load taps between 95 and 1.05%.

As shown in Figure 1, the high and low voltage limits for the 13.8 kV Generator Bus, the 480 Volt Auxiliary Bus, and the 115kV System Bus are interrelated by the tap positions on; the GSU Xfmr, and the AUX Xfmr. Figure 2 shows that the design reactive capability of dual generators is restricted to the area bounded by the A-B-C-E-D. Where: segment AB is limited by the rotor (or field) heating, segment BC is limited by the stator (armature or winding) heating, and segment GE-D is limited by the armature core end heating. Line J-K shows limitation imposed by the Minimum Excitation Limiter (MEL) relay.

Table 1 lists the real and reactive power coordinates for A, B, C, E, J & K from which the radii Ri and centers Opi & Oqi for arcs A-B, B-C and C-E have been determined:

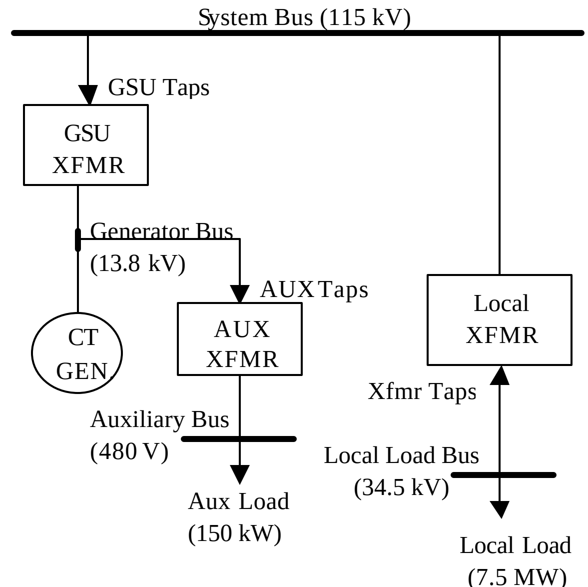

Fig. 1 : One-Line diagram of the CTS.

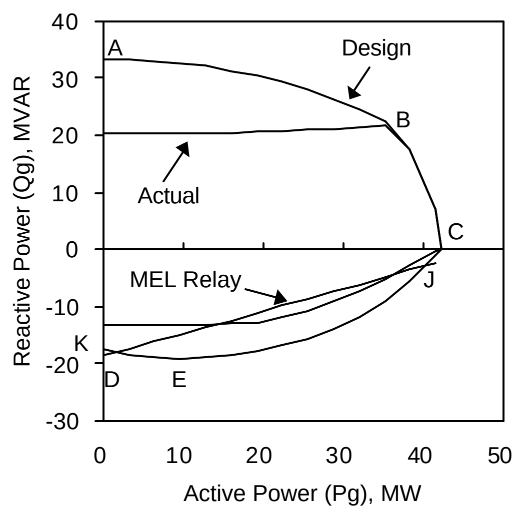

Fig.2: Generator reactive capabilities curves.

$\mathbf{R_1}$= $N_1/(2\cos\alpha)$, $N_1=((Aq-Bq)^2 + Bp^2)^{1/2}$, and $\alpha = \tan^{-1}(Bp/(Aq-Bq))$, $\mathbf{O_{P1}}$ = 0.0, and $\mathbf{O_{q1}}$ = $Aq-R_1$.

$\mathbf{R_2}$= $N_2/(2\cos\beta)$, $N_2=((Cq-Eq)^2+(Cp-Ep)^2)^{1/2}$, and $\beta=\tan^{-1}(Cp-Ep)/(Eq-Cq)$, $\mathbf{O_{P2}}$ = Ep, and $\mathbf{O_{q2}}$ = R_2.

$\mathbf{R_3}$ = $(Bq^2 + Bp^2)^{1/2}$, $\mathbf{O_{P3}}$= 0.0 and $\mathbf{O_{q3}}$ = 0.0.

Table 1. Generator Reactive Capability

	p	q	Arc	Ri	Opi	Oqi
A:	0.0	33.4	A-B:	$\mathbf{R_1}$	$\mathbf{O_{P1}}$	$\mathbf{O_{q1}}$
B:	36.0	22.0		62.5	0.0	–29.1
C:	42.2	0.0	B-C:	$\mathbf{R_2}$	$\mathbf{O_{P2}}$	$\mathbf{O_{q2}}$
E:	10.0	19.0		36.8	10.0	+17.8
J:	40.0	3.0	C-E:	$\mathbf{R_3}$	$\mathbf{O_{P3}}$	$\mathbf{O_{q3}}$
K:	0.0	18.6		42.2	0.0	0.0

The outer curves in Figure 2 are strictly a function of the synchronous machine design parameters. These curves do not consider the actual operating conditions as the limiting factors. The inner curves show the actual operating limits [2]. Using the above R, Op & Oq and Jp,q-Kp,q for a given power output P, the over-and under-excitation limits Q_1, Q_2, Q_3 & Q_4 corresponding to the arcs AB, BC, CE and MEL line JK are determined [1]:

$$Q_1 = Aq - R_1 (1- \cos \delta), \quad \delta = \sin^{-1} (P/R_1),$$
$$Q_2 = R_2 (1- \cos \gamma) - Eq, \quad \gamma = \sin^{-1} ((P-Ep)/R_2)),$$
$$Q_3 = (R_3^2 - P^2)^{1/2}, \text{ and}$$
$$Q_4 = -Jq - (Kq - Jq)(Jp - P)/Jp.$$

The concerns and constraints at the CTS site include: over- and under-excitation of CT generators, tap positions on GSU and AUX transformers, and generator voltage set points.

The SES consists of two 75 MW drum-type boiler-turbine-generator (BTG) units. Each unit has a three-windings standby transformer rated at 38 MVA, 345/4.16 kV, with reactance of 44.5% on 100 MVA base, and no taps, feeding two auxiliary buses, and over twelve auxiliary motors rated between 350 and 6,000 horsepower.

Comparison of the starting and running currents for the auxiliary induction motors shows an increase of several folds. The reactive power requirement during start-up of the 6,000 horsepower induced draft fan motor at typical values of 80% voltage, 20% power factor and 7:1 starting/running current ratio can be estimated to increase to about 30 MVAr. The blackstart source should be able to supply this demand during the 45 seconds of startup duration.

The concern and constraints at the SES site include: the starting over-currents of auxiliary motors, the starting voltage dips of auxiliary buses, and the start-up reactive requirements of motors.

The CTS-STS path between CTS, the blackstart source, and the SES to be started, consists of:
5.2 miles of 115 kV line, one 230/115 kV transformer with five no-load taps (i.e., 230 kV ±5percent), one 180 MVA, 345/230/13.8 kV autotransformer with five no-load taps (i.e., 345 kV ±5percent), and 21.5 miles of 345 kV line with 18.1 MVAr of line charging currents.

The concerns and constraints in the CTS-SES path are to maintain system voltages between 110% and 90%, before and during motor startups, and to select correct tap positions for the 115/230 kV and the 230/345 kV transformers.

5 - MBAL-BASED OPF SOLUTIONS

There are two operating conditions: the motor-off case when the CTS-SES path is energized, and the motor-on case during the 6,000 horsepower motor startup. The former case is referred to as the "light-load" condition, and the latter as the "peak-load" condition. The objectives are to:

- Maximize the reactive power available at the auxiliary bus supplying the 6,000 horsepower motor during the peak-load condition,
- Maintain the same tap positions for GSU Xfmr and AUX Xfmr under light-and peak-load conditions, and
- Keep the same generator voltage set points under light-and peak-load conditions.

The equality constraints are those of a typical power flow case. The inequality constraints are:

- At CTS, the generators bus and auxiliary bus voltages to be within ±5% under both light-and peak-load conditions,
- At CTS, the generator leading reactive power be greater than their minimum excitation limits, (i.e., $-Q \geq -Q_4$), under the light-load condition, and under peak-load condition the generator lagging reactive power be less than their maximum excitation limits, (i.e., $Q \leq Q_1$),
- At SES, the auxiliary bus voltage be greater than 80% under the peak-load and less than 110% under the light-load conditions,
- At SES, the auxiliary bus be able to supply the reactive power required by the 6,000 horsepower motor start up (i.e., $Q \geq 30.4$ MVAr)
- All other bus voltages in the 12-Bus Test System to be between 90% and 110% under Light- or Peak-Load condition.

The MBAL-based OPF used the above equalities and inequalities for both light-and peak-load conditions in one sweep and produced the following solutions:

Table 2. CTS GSU & AUX Xfmer Tap Positions

	Gen	GSU Xfmr	AUX Xfmr
Rating, MVA	42	46	0.3
High Side, kV		118	13.2
Low Side, kV	13.8	14.4	0.48
R, %		0.15	0.0
X, %		7.6	4.99
Base MVA		25	0.3
Tap 1		112100	12540
Tap 2		115050	12870
Tap 3		**118000**	13200
Tap 4		120950	13530
Tap 5		123900	**13860**
Tap 6		126850	-----
RCF, pu		0.9833	0.9565

Table 3. Motor Off/On Voltages

	Gen Bus	CTS AUX	SES AUX
Nominal kV	13.8	0.48	4.16
High Limit, %	105	105	110
Low Limit, %	95	95	80
High Volts, %	**103.3**	**101.0**	**108.7**
Low Volts, %	**103.3**	**98.9**	**82.2**

Table 4. Motor On/Off Load & Generation

	CTS Gen	SES Load
Lag Limit MVAR	31.3	**32.8***
Lead Limit MVAR	-15.4	---
Lag MVAR	**29.7**	**30.4****
Lead MVAR	**-15.6**	---

* Available, ** Requirements

The results are listed in Tables 2, 3 & 4 in **bold** letters. It can be seen that: the tap positions for the GSU and AUX Xfmrs are 118,000 and 13,860 volts, the generator terminal voltages are equal to 103.3 % under motor off and on cases, and the maximum reactive available at the SES AUX bus is equal to 32.80 MVAr.

The listed results in Tables 3 & 4 also show that:

- At CTS, the generator leading reactive power Q = -15.6 ≈ Q_4 = 15.4 MVAr under motor off condition, and the generator lagging reactive power Q = +29.7 < Q_1=31.3 MVAr under motor on condition,
- At SES, the auxiliary bus voltage V=82.2 > 80.0 % under the Motor on and V=108.7 < 110.0 under the motor off conditions, and
- All other bus voltages to are > 90% under motor off and are <110% under motor off on conditions.

6 - VERIFICATION

In order to verify the MBAL-based OPF solution, an interactive power flow (IPF) and the Generator Reactive Capability (GRC) programs were used [1]. The former is utilized to examine the equality constraints and the latter the inequality constraints.

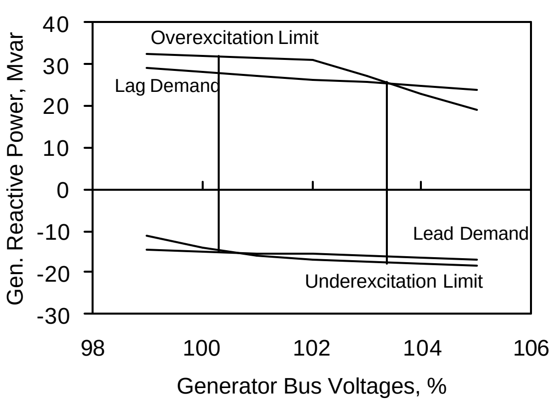

Fig. 3: Generator reactive capabilities & load demand.

Figure 3 shows the CTS generators' leading and lagging reactive power capabilities the blackstart system's leading and lagging reactive power demands. The former is determined by the GRC Program, and the latter by the IPF Program. It can be seen that the lead and lag reactive power demands can be satisfied by having the generator terminal voltage of the CTS generators, between 100.5% and 103.5 %, thus verifying the MBAL-based OPF results.

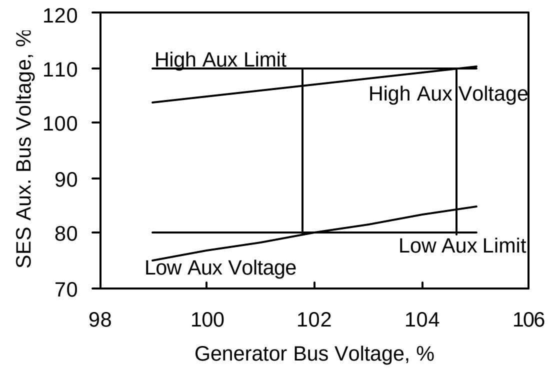

Fig. 4: SES AUX bus high & low voltages vs. limits.

Figure 4 shows the SES auxiliary bus high and low voltage values and the allowable high and low voltage limits of 110 and 80 %. It can be seen that the satisfactory auxiliary bus voltage can be obtained by having the CTS generator terminal voltage between 102.0 and 104.5 %. In order to meet both the reactive power demand and stay within the voltage limits, the generator terminal voltages should be kept between the narrow range of 102.0 to 103.5 %, thus verifying the MBAL- based OPF results.

7 - CONCLUSIONS

The MBAL-based OPF method as shown in the above numerical solutions, has produced very encouraging results. In the process, some shortcomings have also been discovered. The main difficulty is related to the first few Lagrange multipliers update. The necessity to find an approximation for the unconstrained minimizer at each step without well ground stopping criteria makes the initial phase of the computational process time consuming and sometimes difficult. It is important to consider that, generally speaking, the OPFs are not convex optimization problems, which in some cases makes the problem of finding the global unconstrained minimum not an easy task.

The basic features that distinguishes MBAl from the other approaches for addressing large NLP problems are that it:

- Handles problems with both inequality constraints and equations without transforming one set of constraints into the other,
- Does not require the unbounded increase of the barrier-penalty parameter to guarantee convergence as it happens in the Interior Point and Penalty type methods,
- Avoids ill conditioning, i.e. the condition number of the MBAL Hessian is stable when the primal-dual approximation approaches the primal-dual solution, thus in turn, keeping the stable area where Newton's method is well defined,
- Under the standard, second order optimality conditions, it converges with Q-linear rate when the barrier-penalty parameter is fixed. The ratio can

be made as small as desired by choosing a fixed but large enough parameter,

- Eliminates the combinatorial nature of constrained optimization with inequality constraints, and does not require an interior starting point for constrained optimization with inequality constraints.

Briefly, the MBAL-based OPF method was able to: (a) address a major ancillary service, that of providing remote blackstart, (b) optimize generator reactive power supply required by the startup of the large induction motors, and (c) optimally select taps for Transformers directly connected to the generators. The MBAL-based OPF method also showed that alternative solutions such as; installation of shunt reactors or shunt capacitors on the 13.8kV tertiary winding of the 230/345kV transformer, adjustments of on-load tap-changer on the 230/345kV transformer, or installation of on-load tap changers on the GSU and AUX Xfmrs cannot provide a feasible blachstart solution. Because between motor-off and motor-on there is no for taking these corrective actions. Clearly, here is a case where, significant capital expenditures cannot replace what can be achieved by analytical tools such as the MBAL-based OPF.

8 – REFERENCES

[1] M. M. Adibi, D. P. Milaniscz, and T. L. Volkmann, "Remote Cranking of Steam Electric Stations," *IEEE Trans. on Power Systems*, Vol.11, No.4, pp. 1613-1618, August 1996.

[2] M. M. Adibi, D. P. Milanicz, and T. L. Volkmann, "Simulating Transformer Taps for remote Cranking Operations," *IEEE Computer Applications in Power*, July 1996.

[3] M. M. Adibi and D. P. Milanicz, "Reactive Capability Limitation of Synchronous Machines," *IEEE Trans. on Power Systems*, Vol.9, No.1, pp. 29-40, February 1994.

[4] M. M. Adibi, D. P. Milanicz and T.L. Volkmann, "Optimizing Generator Reactive Power Resources," *IEEE Trans. on Power Systems*, Vol.14, No.1, pp. 319-324, February 1999

[5] B. Stott, E. Hobson, "Power System Security Control Calculation Using Linear Programming, Parts I and II," *IEEE Trans. on Power Apparatus and Systems*, Vol. PAS-97, No. 5, pp. 1713-1731, Sept/Oct. 1978.

[6] Task Force on "Interior-Point Method Applications to Power Systems," IEEE-PES Mini Lecture, *Proceedings of PICA'99*, Santa Clara, CA, May 1999.

[7] P. Ristanovic. *Successive Linear Programming Based OPF Solution*. IEEE 96 TP111-0.

[8] I. Nejdawi, K. Clements, P. Davis, "An Efficient Interior Point Method for Sequential Quadratic Programming Based on Optimal Power Flow," *IEEE Trans. on Power Systems*, Vol. 15, No. 4, pp. 1179-1183, 2000.

[9] G. D. Irisarri, X. Wang, J. Tong, and S. Mokhtari, "Maximum Loadability of Power Systems Using Interior Point Non-Linear Optimization Method," *IEEE Trans. on Power Systems*, Vol. 12, pp. 162-172, Feb. 1997.

[10] G. L. Torres and V. H. Quintana, "An Interior-Point Method for Nonlinear Optimal Power Flow using Voltage Rectangular Coordinates," *IEEE Transactions on Power Systems*, Vol. 13, No. 4, pp. 1211-1218, Nov. 1998.

[11] G. Irisarri, L. M. Kimball, K. A. Clements, A. Bagchi, and P. W. Davis, "Economic Dispatch with Network and Ramping Constraints via Interior Point Methods," *IEEE Trans. on Power Systems*, Vol. 13, No. 1, pp. 236-242, Feb. 1998.

[12] J. A. Momoh, S. X. Guo, E. C. Ogbuobiri, and R. Adapa, "The Quadratic Interior Point Method Solving Power System Optimization Problems," *IEEE Trans. on Power Systems*, Vol. 9, No. 3, pp. 1327-1336, Aug. 1994.

[13] S. Wright. *Primal-Dual Interior Points Methods*. SIAM, 1997.

[14] E. Ng, B.W. Peyton, "Block Sparse Cholesky Algorithms on Advanced Uniprocessor Computers," *SIAM Journal of Scientific Computing*, Vol. 14, pp. 1034-1056, 1993.

[15] A. Santos, S. Deckman, and S. Soares, "A Dual Augmented lagrangian Approcah For Optimal Power Flow," *IEEE Transactions on Power Systems*, Vol. 3, No. 3, pp. 1020-1025, Aug. 1988.

[16] R. Vandebei, D. Shanno, "An Interior Point Algorithm for Nonconvex Nonlinear Programming," *Computational Optimization and Applications*, Vol. 13, pp. 231-252, 1999.

[17] M. Shahidehpour and M. Marwali. *Maintenance Scheduling in Restructured Power Systems*. Kluwer Academic Publishers, Norwell, MA. 2000.

[18] R. Polyak, "Modified Barrier Functions," *Mathematical Programming, North Holland,* Vol. 54, pp. 177-222, 1992.

[19] M.J.D. Powell, "A Method for Nonlinear Constraints in Minimization Problems," in *Optimization*, Ed. Fletcher, London. Academic Press, pp. 283-298, 1969.

[20] D. Goldfarb, K. Mints, R. Polyak, I. Yuzefovich, "Modified Barrier-Augmented Lagrangian Method for Constrained Minimization," *Computational Optimization and Applications*, 14, p 55-74, 1999.

[21] S. Nash and J. Nacedal, "A Numerical Study of the Limited Memory BFGS Method and the Truncated-Newton Method or Large Scale Optimization," *SIAM Journal on Optimization*, Vol. 1, pp. 358-372, 1991.

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