An Improved Network Model for Transmission Expansion Planning Considering Reactive Power and Network Losses

Hui Zhang, Student Member, IEEE, Gerald Thomas Heydt, Life Fellow, IEEE, Vijay Vittal, Fellow, IEEE, and Jaime Quintero Member, IEEE

Abstract—The expansion plan obtained from a DC model based transmission expansion planning (TEP) model could be problematic in the AC network because the DC model is potentially inaccurate. However, solving TEP problems using the AC model is still extremely challenging. The motivation for this work is to develop a less relaxed network model, based on which more realistic TEP solutions are obtained. The proposed TEP model includes a linear representation of reactive power, off-nominal bus voltage magnitudes and network losses. Binary variables are added to avoid fictitious losses. Garver’s 6-bus system is used to compare the proposed TEP model with the existing models. An iterative approach for considering the N − 1 criterion during the planning process is developed and demonstrated on the IEEE 118-bus system. Simulation results indicate that the proposed TEP model provides a better approximation to the AC network and is applicable to large power system planning problems.

Index Terms—Linearized AC model, loss modeling, mixed integer second order cone programing, N − 1 contingency modeling, transmission expansion planning.

NOMENCLATURE

\begin{align*}
a_g & : \text{Quadratic cost coefficient of generator } g \\
b_g & : \text{Linear cost coefficient of generator } g \\
b_k & : \text{Series admittance of line } k, \text{ a negative value} \\
b_{k0} & : \text{Shunt admittance of line } k, \text{ a positive value} \\
c_g & : \text{Fixed cost coefficient of generator } g \\
c_k & : \text{Investment cost of the line } k \\
CF_g & : \text{Capacity factor of generator } g \text{ in year } t \\
CG_g & : \text{Hourly energy cost of generator } g \text{ in year } t \\
d & : \text{Discount factor} \\
g_k & : \text{Conductance of line } k, \text{ a positive value} \\
k(l) & : \text{The slope of the } l^{th} \text{ piecewise linear block} \\
M & : \text{Disjunctive factor, a large positive number} \\
P_k & : \text{Active power flow on line } k \\
PD & : \text{Active power demand of load } d \\
PG_g & : \text{Active power generated by generator } g \\
PG_g^{\text{\ max}} & : \text{Maximum active power output of generator } g \\
PG_g^{\text{\ min}} & : \text{Minimum active power output of generator } g \\
PL_k & : \text{Active power loss on line } k \\
Q_k & : \text{Reactive power flow on line } k \\
QD_d & : \text{Reactive power demand of load } d \\
QG_g & : \text{Reactive power generated by generator } g \\
QG_g^{\text{\ max}} & : \text{Maximum reactive power output of generator } g \\
QG_g^{\text{\ min}} & : \text{Minimum reactive power output of generator } g \\
QL_k & : \text{Reactive power loss on line } k \\
S_k^{\text{\ max}} & : \text{MVA rating of line } k \\
TO & : \text{Operating horizon} \\
TP & : \text{Planning horizon} \\
V_i & : \text{Bus voltage magnitude in p.u. at bus } i \\
\Delta V_i & : \text{Voltage magnitude deviation from 1 p.u. at bus } i \\
\Delta V^{\text{\ max}} & : \text{Upper bound on the voltage magnitude deviation} \\
\Delta V^{\text{\ min}} & : \text{Lower bound on the voltage magnitude deviation} \\
z_k & : \text{Binary decision variable for a prospective line } k \\
u(l) & : \text{Binary variable for the } l^{th} \text{ linear block} \\
\delta_k & : \text{Binary variable for modeling } |\theta_k| \\
\theta_k & : \text{Phase angle difference across line } k \\
\theta^{\max} & : \text{Maximum angle difference across a line} \\
\theta^*, \theta' & : \text{Nonnegative slack variables used to replace } \theta_k \\
\Delta \theta_k(l) & : \text{The } l^{th} \text{ linear block of angle difference across line } k \\
\Omega_g & : \text{Set of generators} \\
\Omega_k & : \text{Set of existing lines} \\
\Omega^* & : \text{Set of prospective lines}
\end{align*}

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All the authors are with the School of Electrical, Computer and Energy Engineering, Arizona State University, Tempe, AZ 85287 USA (e-mails: {hui.zhang}, {heydt}, {vijay.vittal} and {jaime.quintero.1}@asu.edu).

I. INTRODUCTION

TRANSMISSION expansion planning (TEP) is regarded as an important research area in power systems and has been studied extensively during the past several decades. The TEP exercise normally focused on improving the reliability and security of the power system when economic impacts were not the primary concern. In contemporary power systems however, the increasing complexity of the network structure and the deregulated market environment have made the TEP problem a complicated decision-making process that requires comprehensive analysis to determine the time, location, and number of transmission facilities that are needed in the future power grid. Building the correct set of transmission lines will not only relieve congestion in the existing network, but will also enhance the overall system reliability and market efficiency.

Various TEP models have been developed during the past
several decades. Among these models, mathematical programming and heuristic methods are two major classes of solution approaches. Heuristic methods are usually not sensitive to the models to be optimized and can potentially examine a large number of candidate solutions. The main criticism of heuristic methods is that most of such methods do not guarantee an optimal solution, and provide few clues regarding the quality of the solution. Mathematical programming methods, on the other hand, can guarantee the optimality of the solution in most cases, but tend to have stricter requirements on the model itself. In order to obtain the global optimal solution efficiently, the problem or at least the continuous relaxation of the problem should be convex. Reference [1] presents a comprehensive review and classification of the available TEP models.

Due to the problem complexity, TEP using the AC network model (ACTEP) is rarely discussed in the literature. The advantage of formulating TEP problems using the AC network model is that the AC model represents the electric power network accurately. Nevertheless, the nonlinear and non-convex nature of the ACTEP model makes the problem difficult to solve and to obtain a globally optimal solution. Reference [2] presented a mixed-integer nonlinear programming (MINLP) approach for solving TEP problems using the AC network model. The interior point method and a constructive heuristic algorithm were employed to solve the relaxed nonlinear programming problem and obtain a good solution. It is reported in [3] that by relaxing the binary variables, a small-scale ACTEP problem can be solved to obtain a local optimal solution. However, solving a MINLP-based ACTEP problem is still extremely challenging.

The DC network model has been used extensively for developing TEP models [4]-[14]. One of the early works, [4] presents a linear programming (LP) approach to solve TEP problems. A mixed integer linear programming (MILP) based disjunctive model in [5] eliminates the nonlinearity caused by the binary decision variables. Based on the disjunctive model, the active power losses were included in [6] and [7]. In [8], the behavior of the demand was modeled through demand-side bidding. A bilevel programming model appears in [9] where the solution to the problem is the Stackelberg equilibrium between two players. A transmission switching coordinated expansion planning model was presented in [10] where the planning problem and the transmission switching problem are solved alternately. The static security constraints are included in [7], [11] and [12]. Regarding to the uncertainty modeling, a two-stage stochastic programming model, which optimizes the mathematical expectation of the weighed future scenarios was proposed in [13] to coordinate the generation and transmission planning. A chance-constrained model was presented in [14] to address the uncertainties of loads and wind farms. This model is by nature a risk-based game in which the planners decide the confidence level at a specified risk.

The DC network model is essentially an approximation of the AC model by relaxing the reactive power and voltage constraints. These relaxations tend to create a “gap” between the solutions obtained from the DC model and the AC model [15]. In some cases, the gap could be large and result in a TEP solution that is problematic in the AC network. It has also been pointed out in [16] and [17] that the LP-based piecewise linear loss model as presented in [6] and [7] may cause the fictitious loss problem under some circumstances. On the other hand, it is still extremely challenging to solve a TEP problem using the AC model. In order to overcome the above difficulties, this paper develops a less relaxed network model, which captures the original AC network more accurately for TEP problems. Contributions of this paper include:

1) Develop a linearized AC model in which reactive power, off-nominal bus voltage magnitudes and network losses are retained. Based on this linearized AC model, a novel TEP formulation (LACTEP) is proposed.

2) Present a MILP formulation for linearized network losses modeling to avoid fictitious losses.

3) Present an iterative approach to incorporate the N – 1 contingency criterion effectively during the planning process.

The remainder of this paper is organized as follows: Section II presents the linearization of the full AC network model. By reformulating the linearized model, the LACTEP model is derived in Section III. In Section IV, the proposed model is validated and compared with other existing models. Concluding remarks are given in Section V.

II. LINEARIZATION OF THE FULL AC MODEL

The approximations made in the traditional DC model significantly simplify the full AC model, but these approximations also degrade the accuracy of the DC model in some cases. In order to improve the model accuracy, the linearized model presented in this section retains a linear representation of reactive power, off-nominal bus voltage magnitudes as well as network losses. The linearization of the line flow equations is essentially based on a Taylor series and the following assumptions are assumed to be valid:

1) The bus voltage magnitudes are always close to 1.0 per unit (p.u.).

2) The angle difference across a line is small so that sin(θ_k) ≈ θ_k and cos(θ_k) ≈ 1 can be applied. This assumption is valid at the transmission level where the active power flow dominates the apparent power flow in the lines.

A. Linearization of the Power Flow Equations

If the effects of phase shifters and off-nominal transformer turns ratios are neglected, the AC power flow in branch k between nodes i and j is written as follows,

\[ P_k = V_i^2 g_k - V_i V_j \left( g_k \cos \theta_k + b_k \sin \theta_k \right) \]  \hspace{1cm} (1a)

\[ Q_k = -V_i^2 (b_k + b_{ij}) + V_i V_j \left( b_k \cos \theta_k - g_k \sin \theta_k \right). \]  \hspace{1cm} (1b)

Based on the first assumption above, the bus voltage magnitude can be written as,

\[ V_i = 1 + \Delta V_i \] \hspace{1cm} (2)

where \(\Delta V_{min} \leq \Delta V_i \leq \Delta V_{max}\) is expected to be small. Substituting (2) into (1a) and (1b) and neglecting higher order terms,
\[ P_l = (1 + 2\Delta V_r) g_k \left( 1 + \Delta V_r + \Delta V_j \right) (g_k + b_k \theta_k) \] (3a)
\[ Q_k = -(1 + 2\Delta V_r) (b_k + b_{0} + (1 + \Delta V_r + \Delta V_j) (b_k - g_k \theta_k). \] (3b)

Notice that (3a) and (3b) still contain nonlinearity. Since \( \Delta V_r \) and \( \theta_k \) are expected to be small, the product \( \Delta V_r \theta_k \) and \( \Delta V_r \theta_k \) can be treated as second order terms and therefore negligible. The linearized power flow equations for line \( k \) metered at bus \( i \) are obtained as follows,
\[ P_{ki}^l = \left( \Delta V_r - \Delta V_j \right) g_k - b_k \theta_k \] (4a)
\[ Q_{ki}^l = -(1 + 2\Delta V_r) b_{0} - \left( \Delta V_j - \Delta V_r \right) b_k - g_k \theta_k. \] (4b)

The power flow for the same line but metered at bus \( j \) is obtained in the same way,
\[ P_{kj}^l = -\left( \Delta V_r - \Delta V_j \right) g_k + b_k \theta_k \] (4c)
\[ Q_{kj}^l = -(1 + 2\Delta V_r) b_{0} + \left( \Delta V_j - \Delta V_r \right) b_k + g_k \theta_k. \] (4d)

Since \( P_k \) and \( Q_k \) are linearized, the MVA limit for line \( k \) can be written as a second-order cone constraint,
\[ P_k^2 + Q_k^2 \leq (S_k^{max})^2. \] (5)

Assuming each generator has a quadratic total cost curve,
\[ CG_k^g = a_g P_k^2 + b_g P_k g + c_g. \] (6)

Notice that (5) and (6) are still convex and can be handled by most commercial linear solvers such as Gurobi [21]. However, if a solver requires both the objective and the constraints to be strictly linear, a piecewise linearized version for (5) and (6) can also be derived.

### B. Linearization of the Losses

Unlike the full AC model that inherently captures the network losses, the network losses for the proposed model, however, need to be modeled separately. Using the second order approximation of \( \cos \theta_k \) and neglecting high order terms, the network losses can be approximated as,
\[ PL_k \approx g_k \theta_k^2 \] (7a)
\[ QL_k \approx -b_k \theta_k^2. \] (7b)

Notice that (7a) and (7b) are still non-convex and need to be piecewise linearized. The following MILP formulation is presented to achieve this objective rigorously:
\[ \theta_k^2 \approx \sum_{l=1}^{L} k(l) \Delta \theta_k(l) \] (8a)

where
\[ \theta_k = \theta_k^+ - \theta_k^- \] (8b)
\[ \sum_{l=1}^{L} \Delta \theta_k(l) = \theta_k^+ + \theta_k^- \] (8c)
\[ 0 \leq \theta_k^+ \leq \delta \theta_{\text{max}} \] (8d)
\[ 0 \leq \theta_k^- \leq (1 - \delta_k) \theta_{\text{max}} \] (8e)

In (8b), two slack variables \( \theta_k^+ \) and \( \theta_k^- \) are used to replace \( \theta_k \). In (8c), the sum of \( \theta_k^+ \) and \( \theta_k^- \) is used to represent \( |\theta_k| \), which is expressed as the summation of a series of linear blocks \( \Delta \theta_k(l) \). Constraints (8d) and (8e) ensure that the right hand side of (8c) equals \( |\theta_k| \), while (8f)-(8h) guarantee that the linear blocks on the left will always be filled up first as illustrated by the shaded area in Fig. 1. The MILP formulation eliminates the fictitious losses using binary variables. However, addition of the binary variables tends to complicate the resultant model and makes its efficient solution difficult when the problem scale is large. Alternatively, a relaxed model can be used by excluding (8g)-(8i) or even (8d) and (8e) to strike a balance between the computation time and model accuracy.

![Fig. 1. Piecewise linearization of \( \theta_k^2 \)](image)

### III. THE LACTEP MODEL

The TEP problem is an extension of the optimal power flow (OPF) problem because it essentially solves a series of OPF problems with different network topologies. In this section, the LACTEP model is developed based on the linearized network model presented in Section II. In this model, it is assumed that the planners have perfect information about the existing network as well as the parameters of the potential lines. Notice that the focus of this paper is to advance network modeling. Therefore, the planning work is carried out at the peak loading hour for a single future scenario. In real world applications, however, multiple scenarios can be developed to account for uncertainties and a two-stage stochastic programming planning model can be readily formulated using the LACTEP model proposed in this paper.

#### A. Objective Function

The objective function used in this paper jointly minimizes the investment cost and the total operating cost,
\[ \min C = \sum_{k \in E_k} c_k z_k (1 + d)^T \] + \[ \sum_{t \in T} \sum_{g \in G_{ns}} 8760CF_{gw} CG_{st} (1 + d)^{-1}. \] (9)

In (9), the first term represents the line investment cost and the second term corresponds to the total operating cost over a time horizon.
horizon scaled by the generator capacity factor, both in million dollars (MS) and are discounted to the present value. Notice that the scaled operating cost model only an estimate of the true operating cost, and can be replaced by a more accurate production cost model if the yearly load profile is available.

As implied by the planning timeline in Fig. 2, all the selected lines are committed in the targeted planning year, and the operating costs are evaluated over multiple years thereafter. In reality, it is difficult to control the choice of the line to be built in a particular year over the planning horizon. Issues such as project review process, construction and the load forecast accuracy could bring too many uncertainties and make the dynamic planning process intractable. This paper is based on a static planning framework and focuses only on the large economic impact of the TEP project. Thus, the incremental economic benefit is lumped into the single targeted planning year.

![Planning timeline](image)

**Fig. 2. Planning timeline**

**B. Power Flow Constraints**

In order to build the TEP model, the linearized power flow equations derived in Section III need to be reformulated. The constraints set related to the power flow equations in the LACTEP model are shown as follows,

\[
P_k = p(\Delta V_i, \theta_k) \quad \forall k \in \Omega_k \tag{10a}
\]

\[
Q_k = q(\Delta V_i, \theta_k) \quad \forall k \in \Omega_k \tag{10b}
\]

\[
(z_k - 1)M \leq P_k - \Delta p(\Delta V_i, \theta_k) \leq (1 - z_k)M \quad \forall k \in \Omega_k \tag{10c}
\]

\[
(z_k - 1)M \leq Q_k - q(\Delta V_i, \theta_k) \leq (1 - z_k)M \quad \forall k \in \Omega_k \tag{10d}
\]

\[-z_k S_k \leq P_k \leq z_k S_k \quad \forall k \in \Omega_k^+ \tag{10e}
\]

\[-z_k S_k \leq Q_k \leq z_k S_k \quad \forall k \in \Omega_k^- \tag{10f}
\]

\[
P_k^2 + Q_k^2 \leq (S_k^\max)^2 \quad \forall k \in \Omega_k \cup \Omega_k^+ \tag{10g}
\]

\[-\theta^\max \leq \theta_k \leq \theta^\max \quad \forall k \in \Omega_k \tag{10h}
\]

\[
(z_k - 1)\pi - \theta^\max \leq \theta_k \leq (1 - z_k)\pi + \theta^\max \quad \forall k \in \Omega_k^+ \tag{10i}
\]

Constraints (10a)-(10d) represent the linearized power flow equations for existing lines and prospective lines, where \(p(\Delta V_i, \theta_k)\) and \(q(\Delta V_i, \theta_k)\) are defined as the right hand side of (4a) and (4b) (or (4c) and (4d)) respectively. For existing lines, the power flow is defined by \(p(\Delta V_i, \theta_k)\) and \(q(\Delta V_i, \theta_k)\). For prospective lines, the disjunctive constraints (10c)-(10d) are used to avoid the nonlinearity that would otherwise appear. The power flow on the potential lines is forced to be zero by (10e) and (10f) if the line is not selected. The line MVA flow is limited by the second-order cone constraint (10g). Constraints (10h) and (10i) put a limit on the phase angle difference across existing lines and prospective lines respectively. If the two buses are directly connected, then \(\theta_k\) is limited by \(\theta^\max\) and \(-\theta^\max\); otherwise, (10i) is not binding.

**C. Network Losses**

The following constraint set extends the concept of linearized loss modeling to the proposed TEP model,

\[
\theta_k = \theta_k^+ - \theta_k^- \quad \forall k \in \Omega_k \cup \Omega_k^+ \tag{11a}
\]

\[
\sum_{i=1}^L \Delta \theta_i(l) = \theta_k^+ + \theta_k^- \quad \forall k \in \Omega_k \cup \Omega_k^+ \tag{11b}
\]

\[
0 \leq \theta_k^+ \leq \delta \theta^\max \quad \forall k \in \Omega_k \tag{11c}
\]

\[
0 \leq \theta_k^- \leq (1 - \delta_k)\theta^\max \quad \forall k \in \Omega_k \tag{11d}
\]

\[
0 \leq \theta_k^+ \leq \delta \theta^\max + (1 - z_k)\pi \quad \forall k \in \Omega_k^+ \tag{11e}
\]

\[
0 \leq \theta_k^- \leq (1 - \delta_k)\theta^\max + (1 - z_k)\pi \quad \forall k \in \Omega_k^+ \tag{11f}
\]

\[
0 \leq \Delta \theta_i(l) \leq \theta^\max / L \quad \forall k \in \Omega_k \tag{11g}
\]

\[
0 \leq \Delta \theta_i(l) \leq \theta^\max / L + (1 - z_k)\pi / L \quad \forall k \in \Omega_k^+ \tag{11h}
\]

\[
PL_k = g_k \sum_{i=1}^L k(l) \Delta \theta_i(l) \quad \forall k \in \Omega_k \tag{11i}
\]

\[
QL_k = -b_k \sum_{i=1}^L k(l) \Delta \theta_i(l) \quad \forall k \in \Omega_k \tag{11j}
\]

\[
0 \leq PL_k \leq z_k g_k (\theta^\max)^2 \quad \forall k \in \Omega_k^+ \tag{11k}
\]

\[
0 \leq PL_k + g_k \sum_{i=1}^L k(l) \Delta \theta_i(l) \leq (1 - z_k)M \quad \forall k \in \Omega_k^+ \tag{11l}
\]

\[
0 \leq QL_k \leq -z_k b_k (\theta^\max)^2 \quad \forall k \in \Omega_k^+ \tag{11m}
\]

\[
0 \leq QL_k - b_k \sum_{i=1}^L k(l) \Delta \theta_i(l) \leq (1 - z_k)M \quad \forall k \in \Omega_k^+ \tag{11n}
\]

\[
\Delta \theta_i(l) \leq \Delta \theta_i(l - 1) \quad \forall k \in \Omega_k \cup \Omega_k^+ \tag{11o}
\]

\[
\theta^\max / L - \Delta \theta_i(l - 1) \leq u_i(l - 1) \theta^\max / L \quad \forall k \in \Omega_k \tag{11p}
\]

\[
z_k \theta^\max / L - \Delta \theta_i(l - 1) \leq u_i(l - 1) \theta^\max / L \quad \forall k \in \Omega_k^+ \tag{11q}
\]

\[
\Delta \theta_i(l) \leq [1 - u_i(l - 1)] \theta^\max / L \quad \forall k \in \Omega_k \cup \Omega_k^+ \tag{11r}
\]

\[
k(l) = (21 - l) \theta^\max / L \quad \forall k \in \Omega_k \cup \Omega_k^+ \tag{11s}
\]

Constraints (11c)-(11i) ensure that the right hand side of (11b) equals \(|\theta|\) for existing lines and the selected prospective lines respectively. Constraints (11g) and (11h) determine the upper and lower bound of a linear block \(\Delta \theta_i(l)\) for existing lines and prospective lines respectively. For existing lines and the selected prospective lines, \(\Delta \theta_i(l)\) is bounded by zero and \(\theta^\max/L\), otherwise, (11h) is not binding. The active and reactive power losses for existing lines are given by (11i) and (11j) respectively. For prospective lines, the active and reactive power losses are determined by (11k)-(11l) and (11m)-(11n) respectively. Constraints (11o)-(11r) guarantee that the linear blocks on the left will be filled up first. Constraints (11a)-(11r) present a full MILP formulation that linearizes the network losses rigorously without generating fictitious losses. Relaxed models can be formed by removing (11o)-(11r) or even (11c)-(11f). The linearized line losses are then split in half and attached to the two terminal buses as “virtual demands”. The terms corresponding to the network losses are added to the nodal balance equations as follows,
\[
\sum_{g \in \mathcal{G}} P_G^g + \sum_{k \in \mathcal{K}} P_{\Delta k} - \sum_{d \in \mathcal{D}} (0.5 P_{L_d}) = \sum_{d \in \mathcal{D}} P_{D_d} \quad (11s)
\]
\[
\sum_{g \in \mathcal{G}} Q_G^g + \sum_{k \in \mathcal{K}} Q_{\Delta k} - \sum_{d \in \mathcal{D}} (0.5 Q_{L_d}) = \sum_{d \in \mathcal{D}} Q_{D_d} \quad (11t)
\]

**D. Generator Capacity Limits**

In the planning study, all the generators in the system are assumed to be on-line. The generator outputs are limited by their minimum and maximum generating capacities as shown in (12a) and (12b). Unit commitment is regarded as an operational problem and is therefore not considered in this model. The generator limits are,

\[
P_{G_{\text{min}}}^g \leq P_{G_{\text{g}}} \leq P_{G_{\text{max}}}^g \quad \forall g \in \Omega_g \quad (12a)
\]
\[
Q_{G_{\text{min}}}^g \leq Q_{G_{\text{g}}} \leq Q_{G_{\text{max}}}^g \quad \forall g \in \Omega_g \quad (12b)
\]

The complete LACTEP model is described by (9)-(12).

**E. Computational Burden and N – 1 Modeling**

The computational burden is a major concern in MIP problems. Typically, increase the number of binary variables could potentially slow the solution process. Therefore, the candidate line set should be carefully selected and only the applicable transmission corridors should be included. With a large-scale MIP problem, the solver may have trouble finding an initial feasible solution. In this case, providing a feasible starting point will help reduce the overall simulation time.

The N – 1 contingency modeling is another major source of the computational burden. In fact, a complete N – 1 analysis in the TEP model for a well-designed power system is generally unnecessary because the number of contingencies that will cause serious overloads is generally limited. The N – 1 modeling approach used in [7] was to explicitly invoke the set of network constraints for all possible operating conditions and satisfy all the constraints when solving the optimization problem. However, the model presented in this paper is more complicated. If the approach in [7] were used, the size of the problem could easily become too large to be solvable. Moreover, the TEP problem uses only a relaxed network model, which means that the solution that satisfies the N – 1 criterion in the TEP model may not represent the actual case in the AC network. In order to make the planned system comply with the N – 1 criterion without imposing too much computational burden, an iterative approach is proposed in Fig. 3.

![Diagram](image)

**IV. ILLUSTRATIVE RESULTS**

In this section, Garver’s 6-bus system and the IEEE 118-bus system are studied and the simulation results are demonstrated. The work presented in this paper is programmed using AMPL [20]. The DC lossless, DC lossy and the LACTEP models are solved by Gurobi 5.0.2 [21]. The ACTEP models are solved by Knitro 8.0 [22]. PowerWorld [23] is used for AC power flow and the N – 1 contingency analysis. All simulations are done on a Linux workstation with an Intel i7-2600, 4-core CPU @ 3.40 GHz with 16 GB of RAM.

**A. Garver’s 6-bus System**

Garver’s 6-bus system has 6 existing lines, 5 loads and 3 generators [2]. Initially, the generator connected at bus 6 is isolated from the main system. The system parameters are listed in Tables I and II. It is assumed that at most 3 lines are allowed in each transmission corridor. The total number of candidate lines is 39. The objective function is to minimize the line investment cost only. The bus voltage magnitude range is 1.00 – 1.05 p.u. The following two cases are analyzed:

1) Case 1: Compare the TEP solutions given by the LACTEP model and other existing models.

2) Case 2: Network losses sensitivity analysis.

**TABLE I CANDIDATE LINE DATA FOR GARVER’S 6-BUS SYSTEM**

<table>
<thead>
<tr>
<th>Corridor</th>
<th>( r_1 ) (p.u.)</th>
<th>( x_1 ) (p.u.)</th>
<th>Capacity (MW)</th>
<th>Cost (M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 2</td>
<td>0.04</td>
<td>0.4</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>1 – 3</td>
<td>0.038</td>
<td>0.38</td>
<td>100</td>
<td>38</td>
</tr>
<tr>
<td>1 – 4</td>
<td>0.06</td>
<td>0.6</td>
<td>80</td>
<td>60</td>
</tr>
<tr>
<td>1 – 5</td>
<td>0.02</td>
<td>0.2</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>1 – 6</td>
<td>0.068</td>
<td>0.68</td>
<td>70</td>
<td>68</td>
</tr>
<tr>
<td>2 – 3</td>
<td>0.02</td>
<td>0.2</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>2 – 4</td>
<td>0.04</td>
<td>0.4</td>
<td>100</td>
<td>40</td>
</tr>
<tr>
<td>2 – 5</td>
<td>0.031</td>
<td>0.31</td>
<td>100</td>
<td>31</td>
</tr>
<tr>
<td>2 – 6</td>
<td>0.03</td>
<td>0.3</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>3 – 4</td>
<td>0.059</td>
<td>0.59</td>
<td>82</td>
<td>59</td>
</tr>
<tr>
<td>3 – 5</td>
<td>0.02</td>
<td>0.2</td>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>3 – 6</td>
<td>0.048</td>
<td>0.48</td>
<td>100</td>
<td>48</td>
</tr>
<tr>
<td>4 – 5</td>
<td>0.063</td>
<td>0.63</td>
<td>75</td>
<td>63</td>
</tr>
<tr>
<td>4 – 6</td>
<td>0.03</td>
<td>0.3</td>
<td>100</td>
<td>30</td>
</tr>
<tr>
<td>5 – 6</td>
<td>0.061</td>
<td>0.61</td>
<td>78</td>
<td>61</td>
</tr>
</tbody>
</table>

**TABLE II GENERATOR AND LOAD DATA FOR GARVER’S 6-BUS SYSTEM**

<table>
<thead>
<tr>
<th>Bus No.</th>
<th>Load parameters</th>
<th>Generator parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>240</td>
<td>-10</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>360</td>
</tr>
<tr>
<td>4</td>
<td>160</td>
<td>-10</td>
</tr>
<tr>
<td>5</td>
<td>240</td>
<td>150</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>200</td>
</tr>
</tbody>
</table>

Using this approach in Fig. 3, the original problem is decomposed into a master problem, which solves the optimization model and a sub-problem, which verifies the network security. The master problem passes the TEP solution and the generator dispatch to the sub-problem, while the sub-problem passes the network violations back to the master problem. The approach solves the two problems iteratively until there is no violation or all the violations identified in the sub-problem are within preset limits.
Case 1: In this case, the TEP solution obtained from the LACTEP model is compared with the solutions obtained from other available TEP models. The full MILP approach is used for modeling the network losses. The number of linear blocks is 7. The comparison results are shown in Table III.

<table>
<thead>
<tr>
<th>TEP model</th>
<th>Expansion plan</th>
<th>Investment cost (M$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC lossless</td>
<td>(3-5), (4-6)x3</td>
<td>110</td>
<td>Need additional reactive power to make the AC power flow converge. Overloads and undervoltage issues are detected.</td>
</tr>
<tr>
<td>DC lossy</td>
<td>(2-6)x3, (3-5)x2</td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>LACTEP</td>
<td>(2-3), (2-6)x2, (3-5)x2, (4-6)x3</td>
<td>210</td>
<td>No additional reactive power needed. All indices are within limits.</td>
</tr>
<tr>
<td>ACTEP [3]</td>
<td>(2-6)x3, (2-3), (3-5)x2, (4-6)x3, (2-5)x2</td>
<td>302</td>
<td></td>
</tr>
</tbody>
</table>

The ACTEP is a non-convex global optimization problem. The result shown in the table is the best solution after five thousand restarts.

The two DC-based TEP models in Table III seem to be superior in the sense that the investment costs are less. However, the reactive power needed for these two models in the AC network actually exceeds the amount that the three generators can supply. In order to make the AC power flow converge, an additional 189 MVAr and 129 MVAr are needed for the DC lossless and the DC lossy model respectively. Meanwhile, overloads and under voltage issues are detected in the system, which require additional investment for network reinforcement. The solution obtained from the LACTEP model requires building more lines than the DC-based models do, but needs no additional reactive power and there are no overloads and undervoltage problems in the AC power flow. The expanded Garver’s 6-bus system with all indices within the preset limits is plotted in Fig. 4.

![Fig. 4. The TEP results of Garver’s 6-bus system](image)

As a non-convex global optimization problem, multiple starting points are tried to obtain a good solution for the ACTEP model. As shown in Table III, the best objective value for the ACTEP model after five thousand restarts is still much higher than the objective function given by the LACTEP model. It will also be computationally too expensive to apply the ACTEP model to larger power system planning problems. This comparison reveals that the solutions given by the DC-based TEP models may not represent the actual case in the AC network and additional network reinforcement is likely to be needed. The LACTEP model better approximates the AC network and therefore provides a more realistic TEP solution.

For small systems such as the 6-bus example, reactive power can be a critical issue to make the AC power flow converge. As indicated by Table III, the LACTEP model chooses to build more lines to provide reactive power support. In reality, increasing generator reactive power capacity and installing VAr support devices can certainly be considered as alternative solutions if a DC-based TEP solution is adopted, but one should be aware that it may not be easy to increase reactive power capacity of existing generators, and can be costly to install VAr support devices at high voltage buses. For real world applications, different solution options can be compared to find the most cost effective TEP plan. For large systems with meshed topology, using LACTEP model is more appropriate because it dispatches generators more accurately, gives a better estimation of line flows, as well as provides a realistic TEP solution, which DC-based models usually fail to do.

Case 2: As discussed in Section II, the linearized network losses can be rigorously modeled using the MILP formulation. However, addition of the binary variables also increases the complexity of the TEP model. The number of linear blocks can significantly affect the solution time as well as the model accuracy. Table IV shows how the number of linear blocks changes the size of the problem and the TEP solution. The full MILP formulation is used for the results shown in Table IV.

<table>
<thead>
<tr>
<th>Linear blocks</th>
<th>Variable types</th>
<th>Objective (M$)</th>
<th>Total P losses (MW)</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>281 Continuous</td>
<td>Infeasible</td>
<td>16.3</td>
<td>&gt; 413</td>
</tr>
<tr>
<td>2</td>
<td>323 Binary</td>
<td>378</td>
<td>8.8</td>
<td>97</td>
</tr>
<tr>
<td>3</td>
<td>407 Continuous</td>
<td>259</td>
<td>11.8</td>
<td>69</td>
</tr>
<tr>
<td>4</td>
<td>449 Binary</td>
<td>230</td>
<td>8.2</td>
<td>89</td>
</tr>
<tr>
<td>5</td>
<td>498 Continuous</td>
<td>230</td>
<td>8.2</td>
<td>33</td>
</tr>
<tr>
<td>6</td>
<td>579 Binary</td>
<td>230</td>
<td>8.2</td>
<td>89</td>
</tr>
<tr>
<td>7</td>
<td>621 Binary</td>
<td>210</td>
<td>8.2</td>
<td>34</td>
</tr>
<tr>
<td>8</td>
<td>666 Binary</td>
<td>210</td>
<td>8.2</td>
<td>43</td>
</tr>
<tr>
<td>9</td>
<td>708 Binary</td>
<td>210</td>
<td>8.2</td>
<td>116</td>
</tr>
<tr>
<td>10</td>
<td>748 Binary</td>
<td>210</td>
<td>8.2</td>
<td>97</td>
</tr>
</tbody>
</table>

The variable types in Table IV show that the size of the problem increases as the number of linear blocks increases. This behavior coincides with the intuition that more variables are needed to model the additional linear blocks. It should be noted that the linearization intrinsically overestimates the losses in the system. If too few linear blocks are used, e.g., 1, then the overestimation can be significant and the problem will be infeasible with the given set of candidate line set. This is reflected from both the trends of losses and the objective values listed in Table IV. It is worth noticing that due to the mixed-integer nature of the problem, the change in solution time does not follow a linear pattern. When too few linear blocks are used, the TEP results may contain unnecessary lines due to the significant overestimation of the network losses. It may also take the solver a long time to branch out an initial feasible so-
olution. On the other hand, too many linear blocks will impose unnecessary computational burden and slow the solution time. The key idea of the study is to find the number of linear blocks that gives the best balance between the model accuracy and the solution time. In this case, 7 is an appropriate number.

The results contained in Table V compare the accuracy of the relaxed losses models and the solution time. The number of linear blocks used for this study is 7.

**TABLE V COMPARISON OF DIFFERENT NETWORK LOSSES MODELS**

<table>
<thead>
<tr>
<th>Losses modeling approach</th>
<th>Total $P$ losses (MW)</th>
<th>Objective (MS)</th>
<th>Time (s)/Δ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full MILP</td>
<td>8.2</td>
<td>210</td>
<td>34/0%</td>
</tr>
<tr>
<td>Relaxation 1 (R1)</td>
<td>10.6</td>
<td>210</td>
<td>20/(-41%)</td>
</tr>
<tr>
<td>Relaxation 2 (R2)</td>
<td>8.4</td>
<td>210</td>
<td>22/(-35%)</td>
</tr>
<tr>
<td>Relaxation 3 (R3)</td>
<td>10.7</td>
<td>210</td>
<td>21/(-38%)</td>
</tr>
<tr>
<td>Do not model losses$^2$</td>
<td>0</td>
<td>150</td>
<td>3/(-91%)</td>
</tr>
</tbody>
</table>

$^1$Full MILP: Use (11a)-(11r) to model the linearized network losses
Relaxation 1: Remove (11o)-(11r)
Relaxation 2: Remove (11c)-(11f)
Relaxation 3: Remove (11c)-(11f) and (11o)-(11r)

$^2$Losses are not modeled, but $P$, $Q$ and $V$ are retained

Among all the loss modeling approaches listed in Table V, the full MILP formulation is the most accurate and serves as a basis of the study. The R1 approach relaxes the constraints for prioritizing the lower linear blocks. This approach reduces the solution time by approximately 41%, but the drawback is that it creates 2.4 MW fictitious active power losses. The R2 approach relaxes the constraints for modeling the absolute value. It reduces the solution time by approximately 35%, and creates only 0.2 MW fictitious losses. The R3 approach relaxes both the constraints that were relaxed in R1 and R2. It reduces the solution time by approximately 38%, but creates 2.5 MW fictitious losses. Additionally, if losses are ignored, the solution time will be significantly reduced by 91%, but the TEP solution no longer satisfies preset the voltage requirement. Except for the no loss case, the TEP solutions remain the same for all other loss modeling approaches. One explanation is that the impact of fictitious losses is not significant enough to change the TEP results in this case. The study results show that the R2 approach is considered as the best trade-off between model accuracy and solution time.

**B. IEEE 118-bus System**

The IEEE 118-bus system [24] is used to demonstrate the potential of applying the proposed LACTEP model to large power systems. The system has 186 existing branches, 54 generators and 91 loads. The line ratings are reduced to create congestions. The system is divided into three zones as shown in Fig. 5 with the zonal data listed in Table VI. The load assumed is the peak loading level. The discount rate is assumed to be 10%, and the number of linear blocks used for loss modeling is 10. The planning horizon is ten years. The objective function jointly minimizes the line investment cost and the scaled ten-year total operating cost. The average capacity factors published in [25] are used in this paper. The capital costs of transmission lines are assumed to be proportional to the length of the lines. Due to the absence of real data, all prospective lines are assumed to share the same corridor and have the same parameters as the existing lines. The planning criteria are given in Table VII. The detailed planning procedure is described in the following steps.

**TABLE VI ZONAL DATA OF THE IEEE 118-bus SYSTEM**

<table>
<thead>
<tr>
<th>Zone</th>
<th>Bus</th>
<th>Branch</th>
<th>Generation (MW)</th>
<th>Load (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>42</td>
<td>62</td>
<td>2280</td>
<td>1865</td>
</tr>
<tr>
<td>Zone 2</td>
<td>48</td>
<td>81</td>
<td>4160</td>
<td>3125</td>
</tr>
<tr>
<td>Zone 3</td>
<td>28</td>
<td>43</td>
<td>2544</td>
<td>1271</td>
</tr>
<tr>
<td>Total</td>
<td>118</td>
<td>186</td>
<td>8884</td>
<td>6261</td>
</tr>
</tbody>
</table>

Fig. 5. Single line diagram of IEEE 118-bus system [24]
### Table VII: TEP Planning Criterion for the IEEE 118-Bus System

<table>
<thead>
<tr>
<th>Voltage (p.u.)</th>
<th>Normal (N – 0)</th>
<th>Contingency (N – 1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.96 ≤ V ≤ 1.06</td>
<td>0.92 ≤ V ≤ 1.06</td>
</tr>
<tr>
<td>Power flow</td>
<td>( P_x^2 + Q_x^2 \leq (S_{max})^2 )</td>
<td>( P_x^2 + Q_x^2 \leq (1.1S_{max})^2 )</td>
</tr>
</tbody>
</table>

### Step 1: Run a regular AC power flow on the system to be planned, and identify the lines that are overloaded or heavily loaded. These lines will form the initial candidate line set.

### Step 2: Use the candidate line set and run the LACTEP model. Obtain the TEP solution and update the system.

### Step 3: Rerun a regular AC power flow on the expanded system and identify any overloaded lines/transformers. Notice that it is still possible to observe some violations in this step because the network model used in the TEP problem is essentially a relaxation of the AC network model. If this happens, one should slightly reduce the line ratings used in the TEP problem and redo Step 2 to Step 3. If no violation is identified in this step, then proceed to Step 4.

### Step 4: Perform a complete N – 1 analysis on the expanded system. Identify the worst contingency and take the line out of service. Form a new candidate line set and return to Step 2. Do this iteratively until all violations are within the preset threshold (as specified in Table VII). It is assumed that the generator dispatch do not change during this process.

The flowchart of the iterative approach is plotted in Fig. 6.

![Flowchart](image)

**Fig. 6.** Flowchart of the iterative approach for considering N – 1 contingency.

Table VIII shows the 15 initial candidate lines and their cost data. The candidate lines for the N – 1 contingency analysis are not included in the table.

### Table VIII: Initial Candidate Lines for the IEEE 118-Bus System

<table>
<thead>
<tr>
<th>No.</th>
<th>Lines</th>
<th>Cost (M$)</th>
<th>No.</th>
<th>Lines</th>
<th>Cost (M$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(3 – 5)</td>
<td>16.2</td>
<td>9</td>
<td>(38 – 37)</td>
<td>6.8</td>
</tr>
<tr>
<td>2</td>
<td>(5 – 6)</td>
<td>9.7</td>
<td>10</td>
<td>(69 – 67)</td>
<td>15.2</td>
</tr>
<tr>
<td>3</td>
<td>(8 – 9)</td>
<td>5.5</td>
<td>11</td>
<td>(77 – 78)</td>
<td>2.8</td>
</tr>
<tr>
<td>4</td>
<td>(8 – 5)</td>
<td>6.0</td>
<td>12</td>
<td>(80 – 99)</td>
<td>30.9</td>
</tr>
<tr>
<td>5</td>
<td>(9 – 10)</td>
<td>5.8</td>
<td>13</td>
<td>(82 – 83)</td>
<td>6.6</td>
</tr>
<tr>
<td>6</td>
<td>(17 – 113)</td>
<td>5.4</td>
<td>14</td>
<td>(94 – 100)</td>
<td>10.4</td>
</tr>
<tr>
<td>7</td>
<td>(23 – 32)</td>
<td>17.3</td>
<td>15</td>
<td>(99 – 100)</td>
<td>14.6</td>
</tr>
<tr>
<td>8</td>
<td>(26 – 30)</td>
<td>15.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The cost of building a transmission line can be roughly estimated by its length, cost per mile and the cost multipliers [26].

Assuming all lines are 230 kV double circuit lines, then the capital cost of a transmission line is calculated as,

\[
C_{line} = 1.5\beta\text{(Line length)}
\]

where 1.5 is cost per mile of 230 kV double circuit lines and \( \beta \) is the transmission length cost multipliers. For lines longer than 10 miles, 3 – 10 miles and shorter than 3 miles, the \( \beta \) values are 1.0, 1.2 and 1.5 respectively. Notice that (13) only gives a rough estimate of the line capital cost, more factors need be included in order to obtain a better estimate. The TEP results are demonstrated in Table IX and X for N – 0 and the N – 1 contingency case respectively.

### Table IX: TEP Results for N – 0

<table>
<thead>
<tr>
<th>Lines to be built</th>
<th>Investment cost (M$)</th>
<th>Total operating cost (M$)</th>
<th>Solution time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(3 – 5), (8 – 9), (9 – 10), (26 – 30)</td>
<td>43</td>
<td>1567.4 (10-year)</td>
<td>4</td>
</tr>
</tbody>
</table>

It is observed from Table IX that four lines need to be added in order to relieve the overloads in the original system with all lines in service (N – 0). The investment cost is 43 M$, and the estimated 10-year total operating cost is 1567.4 M$, which is approximately 156.7 M$ per year. The original system is then expanded using the TEP solution in Table IX and solved using the AC power flow with all indices within the limits. Therefore, with the four lines being added, the system is N – 0 secure. Meanwhile, it is worth mentioning that the TEP solution given by the DC lossless model requires building no line for this case. However, significant overloads and undervoltage issues are observed in the AC power flow.

In order for the system to comply with the N – 1 criterion, the planning process needs to proceed to Step 4. In this case, only line (do not include transformers) contingencies are considered. During the contingency, the monitored violations monitored are overloads, loss of loads as well as undervoltages. The iterative planning process is elaborated in Table X.

### Table X: The Iterative Planning Process for N – 1

<table>
<thead>
<tr>
<th>Iterations</th>
<th>Contingency line</th>
<th>Violation type</th>
<th>Lines added</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(77 – 78)</td>
<td>Line overload</td>
<td>(77 – 78) circuit 2</td>
</tr>
<tr>
<td>2</td>
<td>(80 – 99)</td>
<td>Line overload</td>
<td>(80 – 99) circuit 2</td>
</tr>
<tr>
<td>3</td>
<td>(25 – 27)</td>
<td>Line overload</td>
<td>(23 – 32)</td>
</tr>
<tr>
<td>4</td>
<td>(38 – 65)</td>
<td>Line overload</td>
<td>(30 – 38)</td>
</tr>
<tr>
<td>5</td>
<td>(1 – 3)</td>
<td>Line overload</td>
<td>(1 – 3) circuit 2</td>
</tr>
<tr>
<td>6</td>
<td>(86 – 87)</td>
<td>Line overload</td>
<td>(86 – 87) circuit 2</td>
</tr>
<tr>
<td>7</td>
<td>(64 – 65)</td>
<td>Line overload</td>
<td>(64 – 65) circuit 2</td>
</tr>
<tr>
<td>8</td>
<td>(60 – 61)</td>
<td>Line overload</td>
<td>(60 – 61) circuit 2</td>
</tr>
<tr>
<td>9</td>
<td>(15 – 17)</td>
<td>Line overload</td>
<td>(15 – 17) circuit 2</td>
</tr>
<tr>
<td>10</td>
<td>(12 – 117)</td>
<td>Loss of loads</td>
<td>(12 – 117) circuit 2</td>
</tr>
<tr>
<td>11</td>
<td>(110 – 117)</td>
<td>Loss of loads</td>
<td>(110 – 117) circuit 2</td>
</tr>
</tbody>
</table>

In Table X, the second column lists the lines that are manually outaged in each iteration. The contingencies in the table are ranked in the order of the severity of overload caused in the system. The line that causes severe overloads and results in a large number of associated overloaded lines will be addressed first. The third column shows the type of the violations and the last column provides the solution the potential overloads or loss of loads. After eleven iterations, all indices
are within the limits set in Table VII for the contingency case. The system complies with the $N-1$ contingency criterion. Mathematically, this iterative approach does not guarantee an optimal solution, but in terms of the computational burden, this approach attains the same goal more efficiently.

V. CONCLUSIONS

This paper presents a new approach to linearize the full AC network model, based on which a TEP model is developed. The proposed LACTEP model retains a linear representation of reactive power, off-nominal bus voltage magnitudes and network losses. A MILP formulation for network losses modeling is developed to eliminate fictitious losses. An iterative approach is also presented to incorporate the $N-1$ contingency criterion in TEP problems.

The simulation results of Garver’s 6-bus system show that additional network reinforcements may be needed if a DC-based TEP model is adopted. The proposed LACTEP model, approximates the AC network more accurately, and therefore provides more realistic TEP solutions. The loss modeling sensitivity study shows that the $R_2$ approach tends to give the best trade-off between accuracy and solution time. The fictitious losses are not significant enough to change the TEP results in the 6-bus example studied in this paper. However, this conclusion can be case dependent. The simulation results on the IEEE 118-bus system show that the proposed LACTEP model can be applied to solve large power system planning problems and the iterative approach is a computationally effective way to include the $N-1$ criterion in the TEP study.

VI. ACKNOWLEDGMENT

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VII. REFERENCES


Hui Zhang (S’99) received the B.E degree from Hohai University, Nanjing, China, in 2008 and the M.S. degree from Arizona State University, Tempe, AZ, in 2010, both in electrical engineering. He is currently pursuing the Ph.D. degree at Arizona State University, Tempe.

Gerald T. Heydt (S’62–M’64–SM’80–F’91–LF’08) received the Ph.D. degree in electrical engineering from Purdue University, West Lafayette, IN, in 1970. He is a Regents’ Professor at Arizona State University, Tempe.

Vijay Vittal (S’78–F’97) received the Ph.D. degree from Iowa State University, Ames, IA, in 1982. He is currently the Director of the Power Systems Engineering Research Center (PSERC).

Jaime Quintero (M’06) received the Ph.D. degree in electrical engineering from Washington State University, Pullman, WA, in 2005. Currently, he is a postdoctoral researcher at Arizona State University, Tempe.