Tightening QC Relaxations of AC Optimal Power Flow Problems via Complex Per Unit Normalization

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***Abstract*—Optimal power flow (OPF) is a key problem in power system operations. OPF problems that use the nonlinear AC power flow equations to accurately model the network physics have inherent challenges associated with non-convexity. To address these challenges, recent research has applied various convex relaxation approaches to OPF problems. The QC relaxation is a promising approach that convexifies the trigonometric and product terms in the OPF problem by enclosing these terms in convex envelopes. The accuracy of the QC relaxation strongly depends on the tightness of these envelopes. This paper presents two improvements to these envelopes. The first improvement leverages a polar representation of the branch admittances in addition to the rectangular representation used previously. The second improvement is based on a coordinate transformation via a complex per unit base power normalization that rotates the power flow equations. The trigonometric envelopes resulting from this rotation can be tighter than the corresponding envelopes in previous QC relaxation formulations. Using an empirical analysis with a variety of test cases, this paper suggests an appropriate value for the angle of the complex base power. Comparing the results with a state-of-the-art QC formulation reveals the advantages of the proposed improvements.**

***Index Terms*—Optimal power flow, Convex relaxation**

I. INTRODUCTION

OPTIMAL power flow (OPF) problems are central to many tasks in power system operations. OPF problems optimize an objective function, such as generation cost, subject to both the network physics and engineering limits. The AC power flow equations introduce non-convexities in OPF problems. Due to these non-convexities, OPF problems may have multiple local optima [1] and are generally NP-Hard [2].

Many research efforts have focused on algorithms for obtaining locally optimal or approximate OPF solutions [3]. Recent research has also developed convex relaxations of OPF problems [4]. Convex relaxations bound the optimal objective values, can certify infeasibility, and, in some cases, provably provide globally optimal solutions to OPF problems.

The capabilities of convex relaxations are, in many ways, complementary to those of local solution algorithms. For instance, relaxations' objective value bounds can certify how close a local solution is to being globally optimal. Accordingly, local algorithms and relaxations are used together in spatial branch-and-bound methods [5]. Solutions from relaxations are also useful for initializing some local solvers [6]. Relaxations are also needed for certain solution algorithms for robust OPF problems [7]. Moreover, the objective value bounds provided by relaxations are directly useful in other contexts, e.g., [8], [9]. The tractability and accuracy of these and other algorithms are largely determined by the employed relaxation's tightness. Tightening relaxations is thus an active research topic [4].

The quadratic convex (QC) relaxation is a promising approach that encloses the trigonometric and product terms in the polar representation of power flow equations within convex envelopes [10]. These envelopes are formed with linear and second-order cone programming (SOCP) constraints, resulting in a convex formulation. The QC relaxation's tightness strongly depends on the quality of these convex envelopes. This paper focuses on improving these envelopes.

Previous work has proposed a variety of approaches for tightening the QC relaxation. These include valid inequalities, such as "Lifted Nonlinear Cuts" [11], [12] and constraints that exploit bounds on the differences in the voltage magnitudes [13]. Additionally, since the accuracies of the trigonometric and product envelopes in the QC relaxation rely on the voltage magnitude and angle difference bounds, bound tightening approaches can significantly strengthen the QC relaxation [11], [14]–[16]. When bound tightening approaches provide sign-definite angle difference bounds (i.e., the upper and lower bounds on the angle differences have the same sign), tighter trigonometric envelopes can be applied [11].

This paper proposes two improvements to further tighten QC relaxations of OPF problems. The first improvement leverages a polar representation of the branch admittances in addition to the rectangular representation used in previous QC formulations. Within certain ranges, portions of the trigonometric envelopes resulting from the polar admittance representation are at least as tight (and generally tighter) than the corresponding portions of the envelopes from the rectangular admittance representation. In other ranges, the trigonometric envelopes from the polar admittance representation neither contain nor are contained within the envelopes from the rectangular admittance representation. Thus, combining these envelopes tightens the QC relaxation, with empirical results suggesting limited impacts on solution times.

The polar admittance representation also enables our second improvement. We exploit a degree of freedom in the OPF formulation related to the per unit base power normalization. Selecting a *complex base power* ($S_{base} = |S_{base}|\, e^{j\psi}$) results in a coordinate transformation that rotates the power flow equations relative to the typical choice of a real-valued base power. We leverage the associated rotational degree of freedom ψ to obtain tighter envelopes for the trigonometric functions. While previously proposed power flow algorithms [17] and state estimation algorithms [18] use similar formulations, this paper is, to the best of our knowledge, the first to exploit this

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rotational degree of freedom to improve convex relaxations.

This paper is organized as follows. Sections II and III review the OPF formulation and the previously proposed QC relaxation, respectively. Section IV describes the coordinate changes underlying our improved QC relaxation. Section V then presents these improvements. Section VI empirically evaluates our approach. Section VII concludes the paper.

II. Overview of the Optimal Power Flow Problem

This section formulates the OPF problem using a polar voltage phasor representation. The sets of buses, generators, and lines are $\mathcal{N}$, $\mathcal{G}$, and $\mathcal{L}$, respectively. Let $S_i^d = P_i^d + jQ_i^d$ and $S_i^g = P_i^g + jQ_i^g$ represent the complex load demand and generation, respectively, at bus $i \in \mathcal{N}$, where $j = \sqrt{-1}$. Let V_i and θ_i represent the voltage magnitude and angle at bus $i \in \mathcal{N}$. Let $g_{sh,i} + jb_{sh,i}$ denote the shunt admittance at bus $i \in \mathcal{N}$. For each generator, define a quadratic cost function with coefficients $c_{2,i} \geqslant 0$, $c_{1,i}$, and $c_{0,i}$. For simplicity, we consider a single generator at each bus by setting the generation limits at buses without generators to zero. Upper and lower bounds for all variables are indicated by $(\overline{\cdot})$ and $(\underline{\cdot})$, respectively.

For ease of exposition, each line $(l,m) \in \mathcal{L}$ is modeled as a Π circuit with mutual admittance $g_{lm} + jb_{lm}$ and shunt admittance $jb_{c,lm}$. Extensions to more general line models that allow for off-nominal tap ratios and non-zero phase shifts are straightforward and available in Appendix A. Define $\theta_{lm} = \theta_l - \theta_m$ for $(l,m) \in \mathcal{L}$. The complex power flow into each line terminal $(l,m) \in \mathcal{L}$ is denoted by $P_{lm} + jQ_{lm}$, and the apparent power flow limit is $\overline{S}_{lm}$. The OPF problem is

$$\min \quad \sum_{i \in \mathcal{G}} c_{2,i} \left(P_i^g\right)^2 + c_{1,i}\, P_i^g + c_{0,i} \tag{1a}$$

subject to $\quad (\forall i \in \mathcal{N},\ \forall\, (l,m) \in \mathcal{L})$

$$P_i^g - P_i^d = g_{sh,i}\, V_i^2 + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} P_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} P_{ml}, \tag{1b}$$

$$Q_i^g - Q_i^d = -b_{sh,i}\, V_i^2 + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} Q_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} Q_{ml}, \tag{1c}$$

$$\theta_{ref} = 0, \tag{1d}$$

$$\underline{P}_i^g \leqslant P_i^g \leqslant \overline{P}_i^g, \quad \underline{Q}_i^g \leqslant Q_i^g \leqslant \overline{Q}_i^g, \tag{1e}$$

$$\underline{V}_i \leqslant V_i \leqslant \overline{V}_i, \tag{1f}$$

$$\underline{\theta}_{lm} \leqslant \theta_{lm} \leqslant \overline{\theta}_{lm}, \tag{1g}$$

$$P_{lm} = g_{lm} V_l^2 - g_{lm} V_l V_m \cos\left(\theta_{lm}\right) - b_{lm} V_l V_m \sin\left(\theta_{lm}\right), \tag{1h}$$

$$Q_{lm} = -\left(b_{lm} + b_{c,lm}/2\right) V_l^2 + b_{lm} V_l V_m \cos\left(\theta_{lm}\right) - g_{lm} V_l V_m \sin\left(\theta_{lm}\right), \tag{1i}$$

$$P_{ml} = g_{lm} V_m^2 - g_{lm} V_l V_m \cos\left(\theta_{lm}\right) + b_{lm} V_l V_m \sin\left(\theta_{lm}\right), \tag{1j}$$

$$Q_{ml} = -\left(b_{lm} + b_{c,lm}/2\right) V_m^2 + b_{lm} V_l V_m \cos\left(\theta_{lm}\right) + g_{lm} V_l V_m \sin\left(\theta_{lm}\right), \tag{1k}$$

$$\left(P_{lm}\right)^2 + \left(Q_{lm}\right)^2 \leqslant \left(\overline{S}_{lm}\right)^2, \quad \left(P_{ml}\right)^2 + \left(Q_{ml}\right)^2 \leqslant \left(\overline{S}_{lm}\right)^2. \tag{1l}$$

The objective (1a) minimizes the generation cost. Constraints (1b) and (1c) enforce power balance at each bus. Constraint (1d) sets the reference bus angle, θ_{ref}. The constraints in (1e) bound the active and reactive power generation at each bus. Constraints (1f)–(1g), respectively, bound the voltage magnitudes and voltage angle differences. Constraints (1h)–(1k) relate the active and reactive power flows with the voltage phasors at the terminal buses. The constraints in (1l) limit the apparent power flows into both terminals of each line.

III. The QC Relaxation of the OPF Problem

The QC relaxation convexifies the OPF problem (1) by enclosing the nonconvex terms in convex envelopes [10]. The relevant nonconvex terms are the square V_i^2, $\forall i \in \mathcal{N}$, and the products $V_l V_m \cos(\theta_{lm})$ and $V_l V_m \sin(\theta_{lm})$, $\forall (l,m) \in \mathcal{L}$. The envelope for the generic squared function x^2 is $\langle x^2 \rangle^T$:

$$\langle x^2 \rangle^T = \left\{ \breve{x} : \begin{cases} \breve{x} \geqslant x^2, \\ \breve{x} \leqslant \left(\overline{x} + \underline{x}\right) x - \overline{x}\underline{x}. \end{cases} \right. \tag{2}$$

Envelopes for the generic trigonometric functions $\sin(x)$ and $\cos(x)$ are $\langle \sin(x) \rangle^S$ and $\langle \cos(x) \rangle^C$:

$$\langle \sin(x) \rangle^S = \left\{ \breve{S} : \begin{cases} \breve{S} \leqslant \cos\left(\frac{x^m}{2}\right)\left(x - \frac{x^m}{2}\right) + \sin\left(\frac{x^m}{2}\right) \text{ if } \underline{x} \leqslant 0 \leqslant \overline{x}, \\ \breve{S} \geqslant \cos\left(\frac{x^m}{2}\right)\left(x + \frac{x^m}{2}\right) - \sin\left(\frac{x^m}{2}\right) \text{ if } \underline{x} \leqslant 0 \leqslant \overline{x}, \\ \breve{S} \geqslant \frac{\sin(\underline{x}) - \sin(\overline{x})}{\underline{x} - \overline{x}} \left(x - \underline{x}\right) + \sin\left(\underline{x}\right) \text{ if } \underline{x} \geqslant 0, \\ \breve{S} \leqslant \frac{\sin(\underline{x}) - \sin(\overline{x})}{\underline{x} - \overline{x}} \left(x - \underline{x}\right) + \sin\left(\underline{x}\right) \text{ if } \overline{x} \leqslant 0, \end{cases} \right. \tag{3}$$

$$\langle \cos(x) \rangle^C = \left\{ \breve{C} : \begin{cases} \breve{C} \leqslant 1 - \frac{1 - \cos(x^m)}{(x^m)^2} x^2, \\ \breve{C} \geqslant \frac{\cos(\underline{x}) - \cos(\overline{x})}{\underline{x} - \overline{x}} \left(x - \underline{x}\right) + \cos\left(\underline{x}\right), \end{cases} \right. \tag{4}$$

where $x^m = \max(|\underline{x}|, |\overline{x}|)$. The variables $\breve{S}$ and $\breve{C}$ are associated with the envelopes for the functions $\sin(\theta_{lm})$ and $\cos(\theta_{lm})$. The QC relaxation of the OPF problem in (1) is:

$$\min \quad \sum_{i \in \mathcal{N}} c_{2,i} \left(P_i^g\right)^2 + c_{1,i}\, P_i^g + c_{0,i} \tag{5a}$$

subject to $\quad (\forall i \in \mathcal{N},\ \forall\, (l,m) \in \mathcal{L})$

$$P_i^g - P_i^d = g_{sh,i}\, w_{ii} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} P_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} P_{ml}, \tag{5b}$$

$$Q_i^g - Q_i^d = -b_{sh,i}\, w_{ii} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} Q_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} Q_{ml}, \tag{5c}$$

$$(\underline{V}_i)^2 \leqslant w_{ii} \leqslant (\overline{V}_i)^2, \qquad w_{ii} \in \left\langle V_i^2 \right\rangle^T, \tag{5d}$$

$$P_{lm} = g_{lm} w_{ll} - g_{lm} c_{lm} - b_{lm} s_{lm}, \tag{5e}$$

$$Q_{lm} = -\left(b_{lm} + b_{c,lm}/2\right) w_{ll} + b_{lm} c_{lm} - g_{lm} s_{lm}, \tag{5f}$$

$$P_{ml} = g_{lm} w_{mm} - g_{lm} c_{lm} + b_{lm} s_{lm}, \tag{5g}$$

$$Q_{ml} = -\left(b_{lm} + b_{c,lm}/2\right) w_{mm} + b_{lm} c_{lm} + g_{lm} s_{lm}, \tag{5h}$$

$$\begin{gathered} c_{lm} = \sum_{k=1,\ldots,8} \lambda_k\, \rho_1^{(k)} \rho_2^{(k)} \rho_3^{(k)}, \quad \breve{C}_{lm} \in \left\langle \cos(\theta_{lm}) \right\rangle^C, \\ V_l = \sum_{k=1,\ldots,8} \lambda_k \rho_1^{(k)},\ V_m = \sum_{k=1,\ldots,8} \lambda_k \rho_2^{(k)},\ \breve{C}_{lm} = \sum_{k=1,\ldots,8} \lambda_k \rho_3^{(k)}, \\ \sum_{k=1,\ldots,8} \lambda_k = 1, \quad \lambda_k \geqslant 0, \quad k = 1, \ldots, 8. \end{gathered} \tag{5i}$$

$$\begin{gathered} s_{lm} = \sum_{k=1,\ldots,8} \gamma_k\, \zeta_1^{(k)} \zeta_2^{(k)} \zeta_3^{(k)}, \quad \breve{S}_{lm} \in \left\langle \sin(\theta_{lm}) \right\rangle^S, \\ V_l = \sum_{k=1,\ldots,8} \gamma_k \zeta_1^{(k)},\ V_m = \sum_{k=1,\ldots,8} \gamma_k \zeta_2^{(k)},\ \breve{S}_{lm} = \sum_{k=1,\ldots,8} \gamma_k \zeta_3^{(k)}, \\ \sum_{k=1,\ldots,8} \gamma_k = 1, \quad \gamma_k \geqslant 0, \quad k = 1, \ldots, 8. \end{gathered} \tag{5j}$$

$$P_{lm}^2 + Q_{lm}^2 \leqslant V_l^2\, \ell_{lm}, \tag{5k}$$

$$\ell_{lm} = \left(Y_{lm}^2 - \frac{b_{c,lm}^2}{4}\right) V_l^2 + Y_{lm}^2 V_m^2 - 2Y_{lm}^2 c_{lm} - b_{c,lm} Q_{lm}, \tag{5l}$$

$$\text{Equations (1d)–(1g), (1l), [19, Eq. (9)]}, \tag{5m}$$

where ℓ_{lm} represents the squared magnitude of the current flow into terminal l of line $(l,m) \in \mathcal{L}$. The relationship between ℓ_{lm} and the power flows P_{lm} and Q_{lm} in (5k) tightens the QC relaxation [10], [20]. Appendix A gives an expression for ℓ_{lm} that considers lines with off-nominal tap ratios and non-zero phase shifts. Also, as shown in (5d), w_{ii} is associated with the squared voltage magnitude at bus i.

The lifted variables c_{lm} and s_{lm} represent relaxations of the trilinear terms $V_l V_m \cos(\theta_{lm})$ and $V_l V_m \sin(\theta_{lm})$, respectively, with (5i) and (5j) formulating an "extreme point" representation of the convex hulls for the trilinear terms $V_l V_m \breve{C}_{lm}$ and $V_l V_m \breve{S}_{lm}$ [5]. The auxiliary variables $\lambda_k,\ \gamma_k \in [0,1]$, $k = 1,\ldots,8$, are used in the formulations of these convex hulls. The extreme points of $V_l V_m \breve{C}_{lm}$ are $\rho^{(k)} \in [\underline{V_l}, \overline{V_l}] \times [\underline{V_m}, \overline{V_m}] \times [\underline{\breve{C}}_{lm}, \overline{\breve{C}}_{lm}]$, $k = 1,\ldots,8$ and the extreme points of $V_l V_m \breve{S}_{lm}$ are $\zeta^{(k)} \in [\underline{V_l}, \overline{V_l}] \times [\underline{V_m}, \overline{V_m}] \times [\underline{\breve{S}}_{lm}, \overline{\breve{S}}_{lm}]$, $k = 1,\ldots,8$. Since sine and cosine are odd and even functions, respectively, $c_{lm} = c_{ml}$ and $s_{lm} = -s_{ml}$.

A "linking constraint" from [19, Eq. (9)] is also enforced. This linking constraint is associated with the bilinear terms $V_l V_m$ that are shared in $V_l V_m \cos(\theta_{lm})$ and $V_l V_m \sin(\theta_{lm})$.

IV. Coordinate Transformations

The improvements to the QC relaxation's envelopes that are our main contributions are based on certain coordinate transformations. This section describes these transformations. We first form the power flow equations using polar representations of the lines' mutual admittances. We then introduce a complex base power in the per unit normalization that provides a rotational degree of freedom in the power flow equations.

While this section uses a Π circuit line model for simplicity, extensions to more general line models are straightforward. These extensions are presented in Appendix A.

A. Power Flow Equations with Admittance in Polar Form

Equations (1h)–(1k) model the power flows through a line $(l,m) \in \mathcal{L}$ via a rectangular representation of the line's mutual admittance, $g_{lm} + j b_{lm}$. In (5e)–(5h), the QC relaxation from [10] uses this rectangular admittance representation.

The line flows can be equivalently modeled using a polar representation of the mutual admittance, $Y_{lm} e^{j\delta_{lm}}$, where $Y_{lm} = \sqrt{g_{lm}^2 + b_{lm}^2}$ and $\delta_{lm} = \arctan(b_{lm}/g_{lm})$ are the magnitude and angle of the mutual admittance for line $(l,m) \in \mathcal{L}$, respectively. Using polar admittance coordinates, the complex power flows S_{lm} and S_{ml} into each line terminal are:

$$S_{lm} = V_l e^{j\theta_l} \left(\left(Y_{lm} e^{j\delta_{lm}} + j\frac{b_{c,lm}}{2} \right) V_l e^{j\theta_l} - Y_{lm} e^{j\delta_{lm}} V_m e^{j\theta_m} \right)^{*}, \tag{6a}$$

$$S_{ml} = V_m e^{j\theta_m} \left(-Y_{lm} e^{j\delta_{lm}} V_l e^{j\theta_l} + \left(Y_{lm} e^{j\delta_{lm}} + j\frac{b_{c,lm}}{2} \right) V_m e^{j\theta_m} \right)^{*}, \tag{6b}$$

where $(\cdot)^*$ is the complex conjugate. Taking the real and imaginary parts of (6) yields the active and reactive line flows:

$$P_{lm} = \mathrm{Re}(S_{lm}) = Y_{lm}\cos(\delta_{lm}) V_l^2 - Y_{lm} V_l V_m \cos(\theta_{lm} - \delta_{lm}), \tag{7a}$$

$$Q_{lm} = \mathrm{Im}(S_{lm}) = -\left(Y_{lm}\sin(\delta_{lm}) + b_{c,lm}/2\right) V_l^2 - Y_{lm} V_l V_m \sin(\theta_{lm} - \delta_{lm}), \tag{7b}$$

$$P_{ml} = \mathrm{Re}(S_{ml}) = Y_{lm}\cos(\delta_{lm}) V_m^2 - Y_{lm} V_l V_m \cos(\theta_{lm} + \delta_{lm}), \tag{7c}$$

$$Q_{ml} = \mathrm{Im}(S_{ml}) = -\left(Y_{lm}\sin(\delta_{lm}) + b_{c,lm}/2\right) V_m^2 + Y_{lm} V_l V_m \sin(\theta_{lm} + \delta_{lm}). \tag{7d}$$

With the rectangular admittance representation, the active and reactive power flow equations (1h)–(1i) each have two trigonometric terms (i.e., $\cos(\theta_{lm})$ and $\sin(\theta_{lm})$). Conversely, there is only one trigonometric term in each of the power flow equations that use the polar admittance representation (7) (e.g., $\cos(\theta_{lm} - \delta_{lm})$ for P_{lm} and $\sin(\theta_{lm} - \delta_{lm})$ for Q_{lm}). While these formulations are equivalent, the differing representations of the trigonometric terms suggest the possibility of using different trigonometric envelopes. The QC formulation we will propose in Section V-C exploits these differences.

B. Rotated Power Flow Formulation

The base power used in the per unit normalization is traditionally chosen to be a real-valued quantity. More generally, complex-valued choices for the base power are also acceptable and can provide benefits for some algorithms. For instance, certain power flow [17] and state estimation algorithms [18], [21] leverage formulations with a complex-valued base power.

To improve the QC relaxation's trigonometric envelopes, this section reformulates the OPF problem with a complex base power. Let S_{base}^{orig} and $S_{base}^{new} e^{j\psi}$ denote the original and the new base power, respectively, where S_{base}^{orig}, S_{base}^{new}, and ψ are real-valued. Thus, the original base S_{base}^{orig} is real-valued, while the new base $S_{base}^{new} e^{j\psi}$ is complex-valued with magnitude S_{base}^{new} and angle ψ. Quantities associated with the new base power will be accented with a tilde, $(\tilde{\cdot})$. Complex power flows in the original base and the new base are related as:

$$\tilde{S}_{lm} = S_{lm} \cdot \frac{S_{base}^{orig}}{S_{base}^{new} e^{j\psi}}, \qquad \tilde{S}_{ml} = S_{ml} \cdot \frac{S_{base}^{orig}}{S_{base}^{new} e^{j\psi}}.$$

Since changing the magnitude of the base power does not affect the arguments of the trigonometric functions in the power flow equations, we choose $S_{base}^{new} = S_{base}^{old}$. With this choice,

$$\tilde{S}_{lm} = S_{lm}/e^{j\psi}, \qquad \tilde{S}_{ml} = S_{ml}/e^{j\psi}.$$

The angle of the base power, ψ, affects the arguments of the trigonometric functions, as shown in the following derivation:

$$\tilde{S}_{lm} = S_{lm}/e^{j\psi} = \left(Y_{lm} e^{-j(\delta_{lm}+\psi)} + (b_{c,lm}/2) e^{-j(\frac{\pi}{2}+\psi)} \right) V_l^2 - Y_{lm} V_l V_m e^{j(-\delta_{lm}+\theta_{lm}-\psi)}, \tag{8a}$$

$$\tilde{S}_{ml} = S_{ml}/e^{j\psi} = \left(Y_{lm} e^{-j(\delta_{lm}+\psi)} + (b_{c,lm}/2) e^{-j(\frac{\pi}{2}+\psi)} \right) V_m^2 - Y_{lm} V_m V_l e^{-j(\delta_{lm}+\theta_{lm}+\psi)}. \tag{8b}$$

Taking the real and imaginary parts of (8) yields:

$$\tilde{P}_{lm} = \mathrm{Re}(\tilde{S}_{lm}) = \left(Y_{lm}\cos(\delta_{lm}+\psi) - (b_{c,lm}/2)\sin(\psi)\right)V_l^2 - Y_{lm}V_lV_m\cos(\theta_{lm}-\delta_{lm}-\psi), \tag{9a}$$

$$\tilde{Q}_{lm} = \mathrm{Im}(\tilde{S}_{lm}) = -\left(Y_{lm}\sin(\delta_{lm}+\psi) + (b_{c,lm}/2)\cos(\psi)\right)V_l^2 - Y_{lm}V_lV_m\sin(\theta_{lm}-\delta_{lm}-\psi), \tag{9b}$$

$$\tilde{P}_{ml} = \mathrm{Re}(\tilde{S}_{ml}) = \left(Y_{lm}\cos(\delta_{lm}+\psi) - (b_{c,lm}/2)\sin(\psi)\right)V_m^2 - Y_{lm}V_mV_l\cos(\theta_{lm}+\delta_{lm}+\psi), \tag{9c}$$

$$\tilde{Q}_{ml} = \mathrm{Im}(\tilde{S}_{ml}) = -\left(Y_{lm}\sin(\delta_{lm}+\psi) + (b_{c,lm}/2)\cos(\psi)\right)V_m^2 + Y_{lm}V_mV_l\sin(\theta_{lm}+\delta_{lm}+\psi). \tag{9d}$$

The arguments of the trigonometric functions $\cos(\theta_{lm}-\delta_{lm}-\psi)$, $\sin(\theta_{lm}-\delta_{lm}-\psi)$, $\cos(\theta_{lm}+\delta_{lm}+\psi)$, and $\sin(\theta_{lm}+\delta_{lm}+\psi)$ in (9) are linear in ψ. For a given ψ, all other trigonometric terms in (9) are constants that do not require special handling.

C. Rotated OPF Problem

We next represent the complex power generation and load demands using the new base power:

$$\tilde{S}_i^g = S_i^g \cdot \frac{S_{base}^{orig}}{S_{base}^{new} e^{j\psi}} = \frac{S_i^g}{e^{j\psi}} = \frac{P_i^g + jQ_i^g}{e^{j\psi}}.$$

Define $\tilde{S}_i^g = \tilde{P}_i^g + j\tilde{Q}_i^g$, $\forall i \in \mathcal{N}$. Taking the real and imaginary parts of $\tilde{S}_i^g$ yields the following relationship between the power generation in the new and original bases:

$$\begin{bmatrix}\tilde{P}_i^g \\ \tilde{Q}_i^g\end{bmatrix} = \begin{bmatrix}\cos(\psi) & \sin(\psi) \\ -\sin(\psi) & \cos(\psi)\end{bmatrix}\begin{bmatrix}P_i^g \\ Q_i^g\end{bmatrix}. \tag{10}$$

The inverse relationship is well defined for any choice of ψ since the matrix in (10) is invertible.

The analogous relationship for the power demands is:

$$\begin{bmatrix}\tilde{P}_i^d \\ \tilde{Q}_i^d\end{bmatrix} = \begin{bmatrix}\cos(\psi) & \sin(\psi) \\ -\sin(\psi) & \cos(\psi)\end{bmatrix}\begin{bmatrix}P_i^d \\ Q_i^d\end{bmatrix}. \tag{11}$$

Applying (9)–(11) to (1) yields a "rotated" OPF problem:

$$\min \quad \textstyle\sum_{i\in\mathcal{G}} c_{2,i}\left(\tilde{P}_i^g\cos(\psi) - \tilde{Q}_i^g\sin(\psi)\right)^2 + c_{1,i}\left(\tilde{P}_i^g\cos(\psi) - \tilde{Q}_i^g\sin(\psi)\right) + c_{0,i} \tag{12a}$$

subject to $\quad (\forall i \in \mathcal{N},\ \forall (l,m) \in \mathcal{L})$

$$\tilde{P}_i^g - \tilde{P}_i^d = \left(g_{sh,i}\cos(\psi) - b_{sh,i}\sin(\psi)\right)V_i^2 + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} P_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} P_{ml}, \tag{12b}$$

$$\tilde{Q}_i^g - \tilde{Q}_i^d = -\left(g_{sh,i}\sin(\psi) + b_{sh,i}\cos(\psi)\right)V_i^2 + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} Q_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} Q_{ml}, \tag{12c}$$

$$\theta_{ref} = 0, \tag{12d}$$

$$\underline{P}_i^g \leqslant \tilde{P}_i^g\cos(\psi) - \tilde{Q}_i^g\sin(\psi) \leqslant \overline{P}_i^g, \tag{12e}$$

$$\underline{Q}_i^g \leqslant \tilde{Q}_i^g\cos(\psi) + \tilde{P}_i^g\sin(\psi) \leqslant \overline{Q}_i^g, \tag{12f}$$

$$\underline{V}_i \leqslant V_i \leqslant \overline{V}_i, \qquad \underline{\theta}_{lm} \leqslant \theta_{lm} \leqslant \overline{\theta}_{lm}, \tag{12g}$$

$$(\tilde{P}_{lm})^2 + (\tilde{Q}_{lm})^2 \leqslant (\overline{S}_{lm})^2, \quad (\tilde{P}_{ml})^2 + (\tilde{Q}_{ml})^2 \leqslant (\overline{S}_{lm})^2, \tag{12h}$$

$$\text{Eq. (9).} \tag{12i}$$

The rotated OPF problem (12) is equivalent to (1) in that any solution $\{V^*, \theta^*, \tilde{P}^{g\star}, \tilde{Q}^{g\star}\}$ to (12) can be mapped to a solution $\{V^*, \theta^*, P^{g\star}, Q^{g\star}\}$ to (1) using (10). Solutions to both formulations have the same voltage magnitudes and angles, V^* and θ^*. Thus, (12) can be interpreted as revealing a degree of freedom associated with choosing the base power's phase angle ψ. The next section exploits this degree of freedom to tighten the QC relaxation's trigonometric envelopes.

V. ROTATED QC RELAXATION

This section leverages the coordinate transformations presented in Section IV to tighten the QC relaxation. We first propose and analyze new envelopes for the trigonometric functions and trilinear terms. We then describe an empirical analysis that informs the choice of the base power angle ψ in order to tighten the relaxation for typical OPF problems.

A. Convex Envelopes for the Trigonometric Terms

A key determinant of the QC relaxation's tightness is the quality of the convex envelopes for the trigonometric terms in the power flow equations. The rotated OPF formulation (12) has four relevant trigonometric terms for each line: $\cos(\theta_{lm}-\delta_{lm}-\psi)$, $\sin(\theta_{lm}-\delta_{lm}-\psi)$, $\cos(\theta_{lm}+\delta_{lm}+\psi)$, and $\sin(\theta_{lm}+\delta_{lm}+\psi)$, $\forall (l,m) \in \mathcal{L}$. This contrasts with the two unique trigonometric terms ($\cos(\theta_{lm})$ and $\sin(\theta_{lm})$) per pair of connected buses in the OPF formulation (1).

While this would seem to suggest that at least twice as many convex envelopes would be required for the rotated OPF formulation (12), the arguments of the trigonometric terms in this formulation are not independent. For notational convenience, define $\hat{\delta}_{lm} = \delta_{lm} + \psi$. The angle sum and difference identities imply the following relationships:

$$\begin{bmatrix}\sin(\hat{\delta}_{lm}+\theta_{lm}) \\ \cos(\hat{\delta}_{lm}+\theta_{lm}) \\ \sin(\hat{\delta}_{lm}-\theta_{lm}) \\ \cos(\hat{\delta}_{lm}-\theta_{lm})\end{bmatrix} = \begin{bmatrix}\sin(\hat{\delta}_{lm}) & \cos(\hat{\delta}_{lm}) \\ \cos(\hat{\delta}_{lm}) & -\sin(\hat{\delta}_{lm}) \\ \sin(\hat{\delta}_{lm}) & -\cos(\hat{\delta}_{lm}) \\ \cos(\hat{\delta}_{lm}) & \sin(\hat{\delta}_{lm})\end{bmatrix}\begin{bmatrix}\cos(\theta_{lm}) \\ \sin(\theta_{lm})\end{bmatrix}. \tag{13}$$

Rearranging these relationships yields:

$$\begin{bmatrix}\sin(\theta_{lm}+\hat{\delta}_{lm}) \\ \cos(\theta_{lm}+\hat{\delta}_{lm})\end{bmatrix} = \begin{bmatrix}\alpha_{lm} & \beta_{lm} \\ -\beta_{lm} & \alpha_{lm}\end{bmatrix}\begin{bmatrix}\sin(\theta_{lm}-\hat{\delta}_{lm}) \\ \cos(\theta_{lm}-\hat{\delta}_{lm})\end{bmatrix}. \tag{14}$$

where, for notational convenience, $\alpha_{lm} = (\cos(\hat{\delta}_{lm}))^2 - (\sin(\hat{\delta}_{lm}))^2$ and $\beta_{lm} = 2\cos(\hat{\delta}_{lm})\sin(\hat{\delta}_{lm})$. The implication of (14) is that only two (rather than four) envelopes are defined per line (one for each of the trigonometric terms $\sin(\theta_{lm}-\hat{\delta}_{lm})$ and $\cos(\theta_{lm}-\hat{\delta}_{lm})$). The remaining trigonometric functions, $\sin(\theta_{lm}+\hat{\delta}_{lm})$ and $\cos(\theta_{lm}+\hat{\delta}_{lm})$, are representable in terms of $\sin(\theta_{lm}-\hat{\delta}_{lm})$ and $\cos(\theta_{lm}-\hat{\delta}_{lm})$ via the linear transformation (14). Since the matrix in (14) is invertible for all $\hat{\delta}_{lm}$, the transformation (14) is always well-defined.

Related special consideration is needed for parallel lines. While the rest of this section considers systems without parallel lines for simplicity, Appendix B discusses this issue in detail. Using the linear relationships in (14) (and in (27) from Appendix B for systems with parallel lines), all relevant trigonometric terms in (12) can be represented as linear combinations of $\sin(\theta_{lm}-\delta_{lm}-\psi)$ and $\cos(\theta_{lm}-\delta_{lm}-\psi)$ for each unique pair of connected buses $(l,m) \in \mathcal{L}$.

The corresponding envelopes are $\langle \sin(\theta_{lm} - \delta_{lm} - \psi) \rangle^S$ and $\langle \cos(\theta_{lm} - \delta_{lm} - \psi) \rangle^C$. The QC relaxations of (1) and (12) hence have the same number of envelopes.

There are two characteristics that distinguish the relaxations of the trigonometric expressions in (1) and (12): First, the relaxations of the power flow equations (1h)–(1k) each use the weighted sums of two trigonometric envelopes, while the relaxations of (9a)–(9d) each use a single trigonometric envelope. Second, the base power angle ψ used to formulate (12) provides a degree of freedom that shifts the arguments of the trigonometric envelopes. We next discuss how both of these characteristics can be exploited to tighten the QC relaxation.

Regarding the first distinguishing characteristic, factoring out $-V_l V_m$ to focus on the trigonometric functions shows that the relaxation of (1h) depends on the quality of a weighted sum of trigonometric envelopes: $g_{lm} \langle \cos(\theta_{lm}) \rangle^C + b_{lm} \langle \sin(\theta_{lm}) \rangle^S$. The relaxation of (9a) depends on the quality of the envelope $Y_{lm} \langle \cos(\theta_{lm} - \delta_{lm} - \psi) \rangle^C$. (The relaxations of (1h)–(1k) and (9a)–(9d) are analogous.) To focus on the first characteristic, consider the latter envelope with $\psi = 0$.

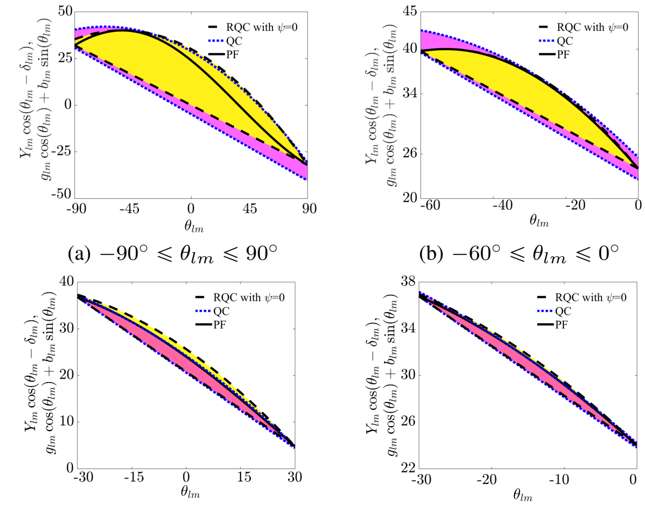
Fig. 1 illustrates examples of these envelopes for a line with the same mutual admittance ($g_{lm} + jb_{lm} = 0.6 - j0.8$) for different intervals of angle differences ($\underline{\theta}_{lm} \leqslant \theta_{lm} \leqslant \overline{\theta}_{lm}$).

To compare these envelopes, we consider their boundaries. As shown in Appendix C, either the upper or lower boundary of the envelope $Y_{lm} \langle \cos(\theta_{lm} - \delta_{lm}) \rangle^C$ is at least as tight (and sometimes tighter) compared to the corresponding boundary of the envelope $g_{lm} \langle \cos(\theta_{lm}) \rangle^C + b_{lm} \langle \sin(\theta_{lm}) \rangle^S$ for certain values of δ_{lm}, θ_{lm}^{min}, and θ_{lm}^{max}. In this case, there is no general dominance relationship for the other boundary. For other values of δ_{lm}, θ_{lm}^{min}, and θ_{lm}^{max}, none of the boundaries of the envelope $Y_{lm} \langle \cos(\theta_{lm} - \delta_{lm}) \rangle^C$ dominate or are dominated by a boundary of the envelope $g_{lm} \langle \cos(\theta_{lm}) \rangle^C + b_{lm} \langle \sin(\theta_{lm}) \rangle^S$. Thus, a QC relaxation that enforces the intersection of these envelopes is generally tighter than relaxations constructed using either of these envelopes individually. Section V-D discusses this further.

The second characteristic distinguishing between the envelopes for (1) and (12) is the ability to choose ψ in the latter envelopes. As shown in Fig. 2, changing ψ rotates the arguments of these envelopes. Analytically comparing the impacts of different values for ψ is not straightforward. Accordingly, this section will later describe an empirical study that suggests a good choice for ψ for typical OPF problems.

B. Envelopes for Trilinear Terms

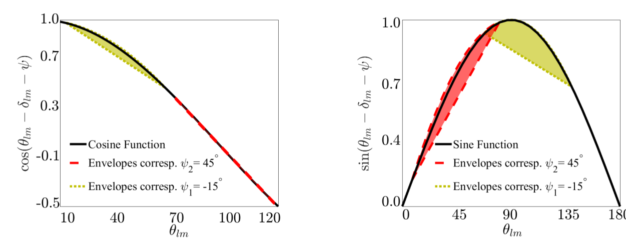
The rotated OPF formulation (12) has four trilinear terms for each line: $V_l V_m \cos(\theta_{lm} - \delta_{lm} - \psi)$, $V_l V_m \sin(\theta_{lm} - \delta_{lm} - \psi)$, $V_l V_m \cos(\theta_{lm} + \delta_{lm} + \psi)$, and $V_l V_m \sin(\theta_{lm} + \delta_{lm} + \psi)$, $\forall (l, m) \in \mathcal{L}$. This contrasts with the two unique trilinear terms ($V_l V_m \cos(\theta_{lm})$ and $V_l V_m \sin(\theta_{lm})$) per pair of connected buses in the OPF formulation (1). This would seem to suggest that at least twice as many envelopes would be required to relax the trilinear terms in the rotated OPF formulation (12). However, the four trilinear terms in (12) are related. We next describe how to exploit these relationships to only enforce two envelopes for the trilinear terms associated with each line.



(a) $-90^\circ \leqslant \theta_{lm} \leqslant 90^\circ$ (b) $-60^\circ \leqslant \theta_{lm} \leqslant 0^\circ$

(c) $-30^\circ \leqslant \theta_{lm} \leqslant 30^\circ$ (d) $-30^\circ \leqslant \theta_{lm} \leqslant 0^\circ$

Figure 1. Comparison of envelopes for the trigonometric terms in (1) and (12). The yellow and magenta regions (with dotted and dashed borders, respectively) in (a)–(d) show the envelopes $g_{lm} \langle \cos(\theta_{lm}) \rangle^C + b_{lm} \langle \sin(\theta_{lm}) \rangle^S$ and $Y_{lm} \langle \cos(\theta_{lm} - \delta_{lm}) \rangle^C$, respectively. The black solid lines correspond to the function $g_{lm} \cos(\theta_{lm}) + b_{lm} \sin(\theta_{lm}) = Y_{lm} \cos(\theta_{lm} - \delta_{lm})$.



(a) $\langle \cos(\theta_{lm} - \delta_{lm} - \psi) \rangle^C$ (b) $\langle \sin(\theta_{lm} - \delta_{lm} - \psi) \rangle^S$

Figure 2. Comparison of envelopes for the sine and cosine functions for different values of ψ. The yellow and red regions (with dashed and dotted borders, respectively) in (a) and (b) show the envelopes $\langle \cos(\theta_{lm} - \delta_{lm} - \psi) \rangle^C$ and $\langle \sin(\theta_{lm} - \delta_{lm} - \psi) \rangle^S$, for $\psi_1 = -15^\circ$ and $\psi_2 = 45^\circ$, respectively. The angle difference θ_{lm} varies within $0^\circ \leqslant \theta_{lm} \leqslant 72^\circ$, and $\delta_{lm} = -53^\circ$.

Similar to (5i)–(5j), we relax the trilinear products by constructing linear envelopes using the upper and lower bounds on V_l, V_m, $\cos(\theta_{lm} - \delta_{lm} - \psi)$, $\sin(\theta_{lm} - \delta_{lm} - \psi)$, $\cos(\theta_{lm} + \delta_{lm} + \psi)$, and $\sin(\theta_{lm} + \delta_{lm} + \psi)$. We use the linear relationship (14) to represent the upper and lower bounds on the receiving end quantities $\cos(\theta_{lm} + \delta_{lm} + \psi)$ (denoted $\underline{\tilde{C}}_{lm}^{(r)}$, $\overline{\tilde{C}}_{lm}^{(r)}$) and $\sin(\theta_{lm} + \delta_{lm} + \psi)$ (denoted $\underline{\tilde{S}}_{lm}^{(r)}$, $\overline{\tilde{S}}_{lm}^{(r)}$) in terms of the bounds on the sending end quantities $\cos(\theta_{lm} - \delta_{lm} - \psi)$ (denoted $\underline{\tilde{C}}_{lm}^{(s)}$, $\overline{\tilde{C}}_{lm}^{(s)}$) and $\sin(\theta_{lm} - \delta_{lm} - \psi)$ (denoted $\underline{\tilde{S}}_{lm}^{(s)}$, $\overline{\tilde{S}}_{lm}^{(s)}$). We then enforce constraints on the sending end quantities derived from the intersection of the transformed bounds associated with the receiving end quantities along with the bounds on the sending end quantities. Intersecting these bounds forms a polytope in terms of the sending end quantities $\tilde{C}_{lm}^{(s)} \in \langle \cos(\theta_{lm} - \delta_{lm} - \psi) \rangle^C$ and $\tilde{S}_{lm}^{(s)} \in \langle \sin(\theta_{lm} - \delta_{lm} - \psi) \rangle^S$, expressible as a convex combination of its extreme points.

Fig. 3 shows the bounds on both the sending and receiving end quantities in terms of the sending end quantities. The yellow region is the polytope formed by the bounds on $\cos(\theta_{lm} - \delta_{lm} - \psi)$ and $\sin(\theta_{lm} - \delta_{lm} - \psi)$. The red region is the polytope formed by using (14) to represent the bounds on the receiving end quantities $\cos(\theta_{lm} + \delta_{lm} + \psi)$ and

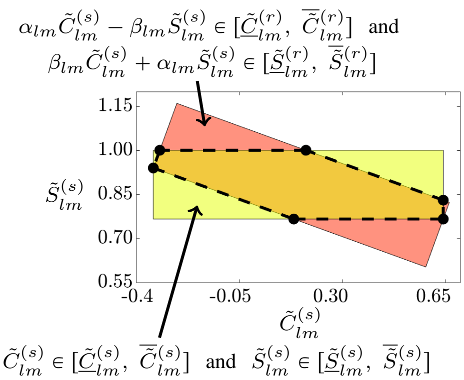


Figure 3. A projection of the four-dimensional polytope associated with the trilinear products between voltage magnitudes and trigonometric functions, in terms of the sending end variables $\tilde{S}_{lm}^{(s)}$ and $\tilde{C}_{lm}^{(s)}$ representing $\cos(\theta_{lm} - \delta_{lm} - \psi)$ and $\sin(\theta_{lm} - \delta_{lm} - \psi)$. The polytope formed by intersecting the sending end polytope (yellow) and receiving end polytope (red) is outlined with the dashed black lines and has vertices shown by the black dots.

$\sin(\theta_{lm} + \delta_{lm} + \psi)$ in terms of the sending end quantities $\cos(\theta_{lm} - \delta_{lm} - \psi)$ and $\sin(\theta_{lm} - \delta_{lm} - \psi)$. The black dots are the vertices of the polytope shown by the dashed black lines formed from the intersection of the yellow and red polytopes. Appendix D shows how to compute these vertices.

Enforcing the constraints associated with both the yellow and red polytopes adds an unnecessary computational burden. We instead restrict the sending end quantities $\cos(\theta_{lm} - \delta_{lm} - \psi)$ and $\sin(\theta_{lm} - \delta_{lm} - \psi)$ to lie within the polytope shown by the black dashed line in Fig. 3. This implicitly ensures satisfaction of the bounds on the receiving end quantities.

To relax the product terms $V_l V_m \cos(\theta_{lm} - \delta_{lm} - \psi)$ and $V_l V_m \sin(\theta_{lm} - \delta_{lm} - \psi)$, we first represent the quantities $\cos(\theta_{lm} - \delta_{lm} - \psi)$ and $\sin(\theta_{lm} - \delta_{lm} - \psi)$ using lifted variables $\tilde{C}_{lm}^{(s)}$ and $\tilde{S}_{lm}^{(s)}$, respectively. We then extend the polytope shown by the black dashed lines in Fig. 3 using the upper and lower bounds on V_l and V_m. The resulting four-dimensional polytope is the convex hull of the quadrilinear polynomial $V_l V_m \tilde{C}_{lm}^{(s)} \tilde{S}_{lm}^{(s)}$, which we represent using an extreme point formulation similar to (5i)–(5j). Let $\mathcal{T}_{lm} = \{(\tilde{C}_{lm}^{int,1}, \tilde{S}_{lm}^{int,1}), (\tilde{C}_{lm}^{int,2}, \tilde{S}_{lm}^{int,2}), \ldots, (\tilde{C}_{lm}^{int,\tilde{N}}, \tilde{S}_{lm}^{int,\tilde{N}})\}$ denote the coordinates of the intersection points (black dots) in Fig. 3, where $\tilde{N}$ is the number of intersection points which ranges from 4 to 8 depending on the value of ψ. The extreme points of $V_l V_m \tilde{C}_{lm}^{(s)} \tilde{S}_{lm}^{(s)}$ are then denoted as $\eta^{(k)} \in [\underline{V_l}, \overline{V_l}] \times [\underline{V_m}, \overline{V_m}] \times \mathcal{T}_{lm}$, $k = 1, \ldots, 4\tilde{N}$. The auxiliary variables $\lambda_k \in [0, 1]$, $k = 1, \ldots, 4\tilde{N}$, are used to form the convex hull of the quadrilinear term $V_l V_m \tilde{C}_{lm}^{(s)} \tilde{S}_{lm}^{(s)}$.

The envelopes for the trilinear terms are:

$$
\begin{aligned}
&\tilde{c}_{lm} = \sum_{k=1,\ldots,4\tilde{N}} \lambda_k\, \eta_1^{(k)} \eta_2^{(k)} \eta_3^{(k)}, \quad \tilde{s}_{lm} = \sum_{k=1,\ldots,4\tilde{N}} \lambda_k\, \eta_1^{(k)} \eta_2^{(k)} \eta_4^{(k)}, \\
&V_l = \sum_{k=1,\ldots,4\tilde{N}} \lambda_k \eta_1^{(k)}, \quad V_m = \sum_{k=1,\ldots,4\tilde{N}} \lambda_k \eta_2^{(k)}, \quad \tilde{S}_{lm}^{(s)} = \sum_{k=1,\ldots,4\tilde{N}} \lambda_k \eta_4^{(k)}, \\
&\tilde{C}_{lm}^{(s)} = \sum_{k=1,\ldots,4\tilde{N}} \lambda_k \eta_3^{(k)}, \quad \sum_{k=1,\ldots,4\tilde{N}} \lambda_k = 1, \quad \lambda_k \geqslant 0, \; k = 1, \ldots, 4\tilde{N}, \\
&\tilde{C}_{lm}^{(s)} \in \langle \cos(\theta_{lm} - \delta_{lm} - \psi) \rangle^C, \; \tilde{S}_{lm}^{(s)} \in \langle \sin(\theta_{lm} - \delta_{lm} - \psi) \rangle^S.
\end{aligned} \tag{15}
$$

Note that (15) precludes the need for the linking constraint in [19, Eq. (9)] that relates the common term $V_l V_m$ in the products $V_l V_m \sin(\theta_{lm})$ and $V_l V_m \cos(\theta_{lm})$.

C. QC Relaxation of the Rotated OPF Problem

Replacing the squared and trilinear terms with the corresponding lifted variables in the rotated OPF formulation (12) results in our proposed "Rotated QC" (RQC) relaxation:

$$\min \quad (12a) \tag{16a}$$

$$\text{subject to} \quad (\forall i \in \mathcal{N}, \forall (l, m) \in \mathcal{L})$$

$$\tilde{P}_i^g - \tilde{P}_i^d = (g_{sh,i} \cos(\psi) - b_{sh,i} \sin(\psi))\, w_{ii} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} \tilde{P}_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} \tilde{P}_{ml}, \tag{16b}$$

$$\tilde{Q}_i^g - \tilde{Q}_i^d = -(g_{sh,i} \sin(\psi) + b_{sh,i} \cos(\psi))\, w_{ii} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } l=i}} \tilde{Q}_{lm} + \sum_{\substack{(l,m)\in\mathcal{L},\\ \text{s.t. } m=i}} \tilde{Q}_{ml}, \tag{16c}$$

$$\tilde{P}_{lm} = (Y_{lm} \cos(\delta_{lm} + \psi) - b_{c,lm}/2 \sin(\psi))\, w_{ll} - Y_{lm} \tilde{c}_{lm}, \tag{16d}$$

$$\tilde{Q}_{lm} = -(Y_{lm} \sin(\delta_{lm} + \psi) + b_{c,lm}/2 \cos(\psi))\, w_{ll} - Y_{lm} \tilde{s}_{lm}, \tag{16e}$$

$$\tilde{P}_{ml} = -Y_{lm} \tilde{c}_{lm} + (Y_{lm} \cos(\delta_{lm} + \psi) - b_{c,lm}/2 \sin(\psi))\, w_{mm}, \tag{16f}$$

$$\tilde{Q}_{ml} = Y_{lm} \tilde{s}_{lm} - (Y_{lm} \sin(\delta_{lm} + \psi) + b_{c,lm}/2 \cos(\psi))\, w_{mm}, \tag{16g}$$

$$\tilde{P}_{lm}^2 + \tilde{Q}_{lm}^2 \leqslant w_{ll}\, \tilde{\ell}_{lm}, \tag{16h}$$

$$
\begin{aligned}
\tilde{\ell}_{lm} = &\Big(b_{c,lm}^2/4 + Y_{lm}^2 - Y_{lm} b_{c,lm} \cos(\delta_{lm} + \psi) \sin(\psi) \\
&+ Y_{lm} b_{c,lm} \sin(\delta_{lm} + \psi) \cos(\psi) \Big) V_l^2 + Y_{lm}^2 V_m^2 \\
&+ \left(-2Y_{lm}^2 \cos(\delta_{lm} + \psi) + Y_{lm} b_{c,lm} \sin(\psi)\right) \tilde{c}_{lm} \\
&+ \left(2Y_{lm}^2 \sin(\delta_{lm} + \psi) + Y_{lm} b_{c,lm} \cos(\psi)\right) \tilde{s}_{lm},
\end{aligned} \tag{16i}
$$

$$\text{Equations (5d), (12d)–(12h), (15).} \tag{16j}$$

Note that trilinear terms in (16) are relaxed via the extreme point approach in (15) that yields the convex hulls for these terms. The variables $\tilde{c}_{lm}$ and $\tilde{s}_{lm}$ are relaxations of the trilinear terms $V_l V_m \cos(\theta_{lm} - \delta_{lm} - \psi)$ and $V_l V_m \sin(\theta_{lm} - \delta_{lm} - \psi)$, respectively. Appendix A gives an expression for $\tilde{\ell}_{lm}$ that considers off-nominal tap ratios and non-zero phase shifts.

D. Tightened QC Relaxation of the Rotated OPF Problem

Applying the angle sum and difference identities in combination with (14) reveals a linear relationship between the trigonometric functions used in the original QC relaxation (5), $\cos(\theta_{lm})$ and $\sin(\theta_{lm})$, and those in the RQC relaxation (16), $\cos(\theta_{lm} - \delta_{lm} - \psi)$ and $\sin(\theta_{lm} - \delta_{lm} - \psi)$:

$$\begin{bmatrix} \cos(\theta_{lm}) \\ \sin(\theta_{lm}) \end{bmatrix} = M_{lm} \begin{bmatrix} \sin(\theta_{lm} - \delta_{lm} - \psi) \\ \cos(\theta_{lm} - \delta_{lm} - \psi) \end{bmatrix}, \tag{17}$$

where the constant matrix M_{lm} is defined as

$$
\begin{aligned}
M_{lm} = \frac{1}{2} \Bigg(&\begin{bmatrix} \sin(\delta_{lm} + \psi) & \cos(\delta_{lm} + \psi) \\ \cos(\delta_{lm} + \psi) & -\sin(\delta_{lm} + \psi) \end{bmatrix} \begin{bmatrix} \alpha_{lm} & \beta_{lm} \\ -\beta_{lm} & \alpha_{lm} \end{bmatrix} \\
&+ \begin{bmatrix} -\sin(\delta_{lm} + \psi) & \cos(\delta_{lm} + \psi) \\ \cos(\delta_{lm} + \psi) & \sin(\delta_{lm} + \psi) \end{bmatrix} \Bigg)
\end{aligned}
$$

with α_{lm} and β_{lm} defined as in (14). As mentioned in Section V-A, the RQC relaxation (16) can be further tightened by additionally enforcing the envelopes $\langle\cos(\theta_{lm})\rangle^C$ and $\langle\sin(\theta_{lm})\rangle^S$ used in the original QC relaxation (5). This results in the "Tightened Rotated QC" (TRQC) relaxation:

$$\min \quad (12a) \tag{18a}$$

$$\text{subject to} \quad (\forall i \in \mathcal{N}, \forall (l,m) \in \mathcal{L})$$

$$M_{lm}\begin{bmatrix}\tilde{C}_{lm}^{(s)}\\ \tilde{S}_{lm}^{(s)}\end{bmatrix} \in \begin{bmatrix}\langle\cos(\theta_{lm})\rangle^C\\ \langle\sin(\theta_{lm})\rangle^S\end{bmatrix} \tag{18b}$$

$$\text{Equations (5d), (12d)–(12h), (15), (16b)–(16i).} \tag{18c}$$

E. An Empirical Analysis for Determining the Rotation ψ

The key parameter in our proposed QC formulation is the rotation ψ. We next describe an empirical analysis for choosing a value for ψ that works well for a range of test cases.

Fig. 4 shows the optimality gaps for the PGLib-OPF test cases as a function of ψ, each normalized by the maximum gap for that case over all values for ψ. The results in the figure were generated by sweeping ψ from -90° to 90° in steps of 0.5°. (The figure is exactly symmetric for values of ψ from 90° to -90°.) The shaded red bands around the median line (in black) show every fifth percentile of the results. The best value of ψ for each case is denoted as ψ^*.

The results in Fig. 4 indicate that good values of ψ are consistent across the test systems. Thus, we suggest using $\psi = 80^\circ$, which is where the median of the optimality gaps over all the test cases was smallest. Moreover, the symmetry in Fig. 4 implies that selecting ψ within the intervals $[-90^\circ, -80^\circ]$, $[-15^\circ, -5^\circ]$, and $[80^\circ, 90^\circ]$ results in nearly the smallest optimality gaps for almost all of the test cases compared to the optimality gaps from the RQC relaxation using ψ^*.

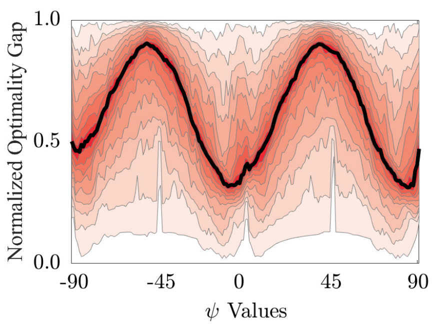


Figure 4. Normalized optimality gap as a function of ψ for PGLib-OPF cases.

VI. Numerical Results

This section demonstrates the effectiveness of the proposed approach using selected test cases from the PGLib-OPF v18.08 benchmark library [22]. These test cases were selected since existing relaxations fail to provide tight bounds on the best known objective values. Our implementations use Julia 0.6.4, JuMP v0.18 [23], PowerModels.jl [24], and Gurobi 8.0 as modeling tools and the solver. The results are computed using a laptop with an i7 1.80 GHz processor and 16 GB of RAM.

Table I summarizes the results from applying the QC (5), RQC (16), and TRQC (18) relaxations to selected test cases. The first column lists the test cases. The next group of columns represents optimality gaps, defined as

$$\textit{Optimality Gap} = \left(\frac{\textit{Local Solution} - \textit{QC Bound}}{\textit{Local Solution}}\right). \tag{19}$$

The optimality gaps are defined using the local solutions to the non-convex problem (1) from PowerModels.jl. The final group of columns shows the solver times.

Comparing the second and third columns in Table I reveals that using admittances in polar form without rotation (i.e., the RQC relaxation (16) with $\psi = 0$) can improve the optimality gaps of some test cases (e.g., improvements of 3.76% and 3.19% for "case30_ieee" and "case24_ieee_rts__api", respectively, relative to the original QC relaxation (5)) . However, the RQC relaxation with $\psi = 0$ has worse performance in other cases, such as "case300_ieee" and "case14_ieee__sad", which have 0.02% and 2.29% larger optimality gaps, respectively.

Using a non-zero value for ψ can improve the optimality gaps. Solving the RQC relaxation (16) with the suggested $\psi = 80^\circ$ obtained from the empirical analysis in Section V-E results in 1.08% better optimality gaps, on average, compared to the original QC relaxation. The RQC relaxation (16) with ψ^* (the best value of ψ for each case) provides optimality gaps that are not worse than those obtained by the original QC relaxation (5) for all test cases, yielding an improvement of 1.36% on average compared to the original QC relaxation. As one specific example, the gap from the original QC relaxation for "case162_ieee_dtc__sad" is 6.22% compared to 6.30% for the RQC relaxation (16) with $\psi = 0$ relaxation (16). Use of the suggested $\psi = 80^\circ$ reduces the gap to 5.65%, which is superior to the gap obtained from the QC relaxation (5). Using ψ^* further reduces the optimality gap to 5.59%.

Enforcing the envelopes from both the original QC relaxation and the RQC relaxation, i.e., the TRQC relaxation (18), further improves the optimality gaps. Solving the TRQC relaxation (18) with the suggested $\psi = 80^\circ$ results in 1.29% better gaps, on average, compared to the original QC relaxation. The TRQC relaxation with ψ^* yields optimality gaps that are 1.57% and 0.21% better, on average, compared to the original QC relaxation and the RQC relaxation with ψ^*. The additional envelopes $\langle\sin(\theta_{lm})\rangle^S$ and $\langle\cos(\theta_{lm})\rangle^C$ in the TRQC relaxation increase the average solver time by 22%.

Fig. 5 visualizes the optimality gaps for variants of the QC relaxation over a range of test cases. Positive values indicate an improvement in the optimality gap of the associated variant relative to the original QC relaxation (5). The test cases are sorted in order of increasing optimality gaps obtained from the original QC relaxation. The TRQC relaxation with ψ^* achieves the smallest optimality gaps. While the RQC relaxation with $\psi = 0$ obtains a worse optimality gap for some test cases compared to the original QC relaxation, both the RQC and TRQC relaxations with ψ^* outperform the QC relaxation for all test cases. As expected from the analysis in Section V-E, applying the suggested $\psi = 80^\circ$ results in good performance across a variety of test cases.

VII. Conclusion

This paper proposes and empirically tests two improvements for strengthening QC relaxations of OPF problems by tightening the envelopes used for the trigonometric terms. The first improvement represents the line admittances in polar form. The second improvement applies a complex base power normalization with angle ψ in order to rotate the arguments

Table I
RESULTS FROM APPLYING THE QC AND RQC RELAXATIONS WITH VARIOUS OPTIONS TO SELECTED PGLIB TEST CASES

Test Cases	QC Gap (%)	RQC ($\psi = 0$) Gap (%)	RQC ($\psi = 80^\circ$) Gap (%)	RQC (ψ*)		TRQC ($\psi = 80^\circ$) Gap (%)	TRQC (ψ*)		QC Time (sec)	RQC Time (sec)	TRQC Time (sec)
				Gap (%)	ψ*		Gap (%)	ψ*			
case3_lmbd	0.97	0.97	0.89	0.79	-81°	0.84	0.63	11°	0.34	0.01	0.01
case30_ieee	18.67	14.91	13.14	12.11	65°	13.14	11.82	-25°	0.33	0.03	0.03
case118_ieee	0.77	0.90	0.65	0.64	70°	0.64	0.62	70°	0.55	0.19	0.23
case300_ieee	2.56	2.58	2.43	2.26	-13°	2.32	2.24	-13°	1.54	1.50	3.15
case9241_pegase	1.71	1.70	1.70	1.69	-10°	1.70	1.69	-10°	265.39	190.80	297.56
case3_lmbd__api	4.57	4.31	4.42	4.28	2°	4.17	3.93	-71°	0.51	0.01	0.01
case24_ieee_rts__api	11.02	7.83	7.51	7.24	79°	7.31	6.98	-11°	0.71	0.03	0.04
case39_epri__api	1.71	1.38	1.33	1.33	-11°	1.32	1.32	79°	0.39	0.05	0.05
case73_ieee_rts__api	9.54	8.12	7.36	7.36	-10°	7.24	7.24	-10°	1.00	0.29	0.37
case118_ieee__api	28.67	28.03	26.82	26.52	-8°	27.11	26.38	-8°	0.53	0.20	0.97
case179_goc__api	5.86	6.01	5.57	4.90	-81°	4.90	4.06	-78°	0.82	0.61	0.64
case14_ieee__sad	19.16	21.45	17.89	16.30	77°	15.82	15.39	-12°	0.35	0.03	0.03
case24_ieee_rts__sad	2.74	2.55	2.31	2.19	78°	2.26	2.12	-12°	0.40	0.05	0.06
case30_ieee__sad	5.66	5.95	4.81	4.59	-13°	4.56	4.45	66°	0.32	0.05	0.06
case73_ieee_rts__sad	2.37	2.24	1.98	1.90	79°	1.84	1.82	78°	0.41	0.28	0.41
case118_ieee__sad	6.67	8.10	5.45	5.39	81°	5.45	5.07	69°	0.58	0.25	0.39
case162_ieee_dtc__sad	6.22	6.30	5.65	5.59	-14°	5.65	5.54	76°	0.86	0.55	0.84
case300_ieee__sad	2.34	2.59	1.80	1.61	83°	1.78	1.59	83°	1.94	1.29	2.06

AC: AC local solution from (1), *QC Gap*: Optimality gap for the QC relaxation from (5), *RQC Gap*: Optimality gap for the Rotated QC relaxation from (16), *TRQC Gap*: Optimality gap for the Tightened Rotated QC Relaxation from (18), ψ*: Use of the best ψ for this case.

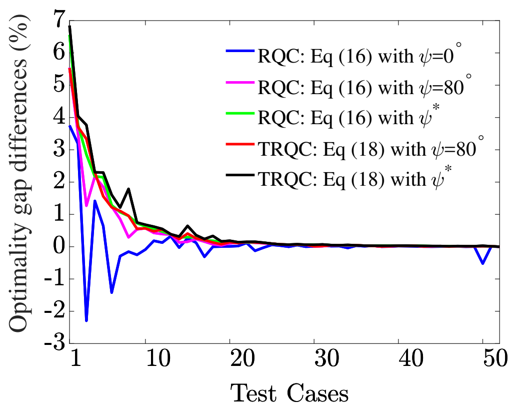


Figure 5. Comparison of optimality gap differences with respect to the original QC relaxation (5) for different QC relaxation variants.

of the trigonometric terms. An empirical analysis is used to suggest a good value for ψ. Comparison to the state-of-the-art QC relaxation reveals the effectiveness of the proposed improvements. Our ongoing work is extending the RQC relaxation to allow for distinct values of ψ for each line.

APPENDIX

A. More General Line Models

This appendix extends the paper's results to a line model that considers transformers with a non-zero phase shift θ_{lm}^{shift} and/or an off-nominal voltage ratio τ_{lm}. With this model, the complex power flows into both terminals of line $(l, m) \in \mathcal{L}$ are:

$$S_{lm} = V_l e^{j\theta_l}\left[\left(Y_{lm}e^{j\delta_{lm}} + j\frac{b_{c,lm}}{2}\right)\frac{V_l e^{j\theta_l}}{\tau_{lm}^2} - \frac{Y_{lm}e^{j\delta_{lm}}V_m e^{j\theta_m}}{\tau_{lm}e^{-j\theta_{lm}^{shift}}}\right]^* \tag{20a}$$

$$S_{ml} = V_m e^{j\theta_m}\left[\left(Y_{lm}e^{j\delta_{lm}} + j\frac{b_{c,lm}}{2}\right)V_m e^{j\theta_m} - \frac{Y_{lm}e^{j\delta_{lm}}V_l e^{j\theta_l}}{\tau_{lm}e^{j\theta_{lm}^{shift}}}\right]^* \tag{20b}$$

We follow the procedure in Section IV-B by applying a complex base power normalization:

$$\tilde{S}_{lm} = \frac{S_{lm}}{e^{j\psi}} = \left(\frac{Y_{lm}}{\tau_{lm}^2}e^{-j(\delta_{lm}+\psi)} + \frac{b_{c,lm}}{2}\frac{e^{-j(\frac{\pi}{2}+\psi)}}{\tau_{lm}^2}\right)V_l^2 - \frac{Y_{lm}}{\tau_{lm}}V_l V_m e^{j(\theta_{lm}-\delta_{lm}-\theta_{lm}^{shift}-\psi)}, \tag{21a}$$

$$\tilde{S}_{ml} = \frac{S_{ml}}{e^{j\psi}} = \left(Y_{lm}e^{-j(\delta_{lm}+\psi)} + \frac{b_{c,lm}}{2}e^{-j(\frac{\pi}{2}+\psi)}\right)V_m^2 - \frac{Y_{lm}}{\tau_{lm}}V_l V_m e^{j(-\theta_{lm}-\delta_{lm}+\theta_{lm}^{shift}-\psi)}. \tag{21b}$$

Taking the real and imaginary parts of (21) yields:

$$\tilde{P}_{lm} = \mathrm{Re}(\tilde{S}_{lm}) = \left(\frac{Y_{lm}}{\tau_{lm}^2}\cos(\delta_{lm}+\psi) - \frac{b_{c,lm}}{2\tau_{lm}^2}\sin(\psi)\right)V_l^2 - \frac{Y_{lm}}{\tau_{lm}}V_l V_m\cos(\theta_{lm}-\delta_{lm}-\theta_{lm}^{shift}-\psi), \tag{22a}$$

$$\tilde{Q}_{lm} = \mathrm{Im}(\tilde{S}_{lm}) = \left(-\frac{Y_{lm}}{\tau_{lm}^2}\sin(\delta_{lm}+\psi) - \frac{b_{c,lm}}{2\tau_{lm}^2}\cos(\psi)\right)V_l^2 - \frac{Y_{lm}}{\tau_{lm}}V_l V_m\sin(\theta_{lm}-\delta_{lm}-\theta_{lm}^{shift}-\psi), \tag{22b}$$

$$\tilde{P}_{ml} = \mathrm{Re}(\tilde{S}_{ml}) = \left(Y_{lm}\cos(\delta_{lm}+\psi) - \frac{b_{c,lm}}{2}\sin(\psi)\right)V_m^2 - \frac{Y_{lm}}{\tau_{lm}}V_m V_l\cos(\theta_{lm}+\delta_{lm}-\theta_{lm}^{shift}+\psi), \tag{22c}$$

$$\tilde{Q}_{ml} = \mathrm{Im}(\tilde{S}_{ml}) = \left(-Y_{lm}\sin(\delta_{lm}+\psi) - \frac{b_{c,lm}}{2}\cos(\psi)\right)V_m^2 + \frac{Y_{lm}}{\tau_{lm}}V_m V_l\sin(\theta_{lm}+\delta_{lm}-\theta_{lm}^{shift}+\psi). \tag{22d}$$

The arguments of the trigonometric terms in (22) are not independent since $\cos(\theta_{lm}+\delta_{lm}-\theta_{lm}^{shift}+\psi)$ and $\sin(\theta_{lm}+\delta_{lm}-\theta_{lm}^{shift}+\psi)$ are linearly related with $\cos(\theta_{lm}-\delta_{lm}-\theta_{lm}^{shift}-\psi)$ and $\sin(\theta_{lm}-\delta_{lm}-\theta_{lm}^{shift}-\psi)$ via the general form of (14). Extending (14) to consider off-nominal voltage ratios and non-zero phase shifts is accomplished by replacing θ_{lm} in (14) with $\theta_{lm} - \theta_{lm}^{shift}$.

Extensions of the expressions for the squared magnitudes of the current flows in the original QC relaxation (5) and the RQC relaxation (16), ℓ_{lm} and $\tilde{\ell}_{lm}$, respectively, are derived by dividing $(P_{lm}^2 + Q_{lm}^2)$ and $(\tilde{P}_{lm}^2 + \tilde{Q}_{lm}^2)$ by V_l^2:

$$\ell_{lm} = \left(\frac{Y_{lm}^2}{\tau_{lm}^4} - \frac{b_{c,lm}^2}{4\tau_{lm}^4}\right) V_l^2 + \frac{Y_{lm}^2}{\tau_{lm}^2} V_m^2 - \frac{b_{c,lm}}{\tau_{lm}^2} Q_{lm} \\ - 2\frac{Y_{lm}^2}{\tau_{lm}^3}\left(\cos(\delta_{lm}) c_{lm} + \sin(\delta_{lm}) s_{lm}\right), \tag{23}$$

$$\tilde{\ell}_{lm} = \left(\frac{Y_{lm}^2}{\tau_{lm}^4} + \frac{b_{c,lm}^2}{4\tau_{lm}^4} - \frac{Y_{lm}}{\tau_{lm}^4} b_{c,lm}\cos(\delta_{lm}+\psi)\sin(\psi) \right. \\ \left. + \frac{Y_{lm}}{\tau_{lm}^4} b_{c,lm}\sin(\delta_{lm}+\psi)\cos(\psi)\right) V_l^2 + \frac{Y_{lm}^2}{\tau_{lm}^2} V_m^2 \\ + \left(\frac{Y_{lm}}{\tau_{lm}^3} b_{c,lm}(\sin(\psi) - \frac{2Y_{lm}^2}{\tau_{lm}^3}\cos(\delta_{lm}+\psi)\right)\tilde{c}_{lm} \\ + \left(\frac{Y_{lm}}{\tau_{lm}^3} b_{c,lm}\cos(\psi) + \frac{2Y_{lm}^2}{\tau_{lm}^3}\sin(\delta_{lm}+\psi)\right)\tilde{s}_{lm} \tag{24}$$

Extending the TRQC relaxation (18) to the more general line model is achieved by modifying (17):

$$\begin{bmatrix}\cos(\theta_{lm})\\ \sin(\theta_{lm})\end{bmatrix} = M'_{lm}\begin{bmatrix}\sin(\theta_{lm} - \delta_{lm} - \psi - \theta_{lm}^{shift})\\ \cos(\theta_{lm} - \delta_{lm} - \psi - \theta_{lm}^{shift})\end{bmatrix}, \tag{25}$$

where the constant matrix M'_{lm} is defined as

$$M'_{lm} = \frac{1}{2}\left(\begin{bmatrix}-\sin(\hat{\delta}_{lm} + \theta_{lm}^{shift}) & \cos(\hat{\delta}_{lm} + \theta_{lm}^{shift})\\ \cos(\hat{\delta}_{lm} + \theta_{lm}^{shift}) & \sin(\hat{\delta}_{lm} + \theta_{lm}^{shift})\end{bmatrix}\right. \\ \left. + \begin{bmatrix}\sin(\hat{\delta}_{lm} - \theta_{lm}^{shift}) & \cos(\hat{\delta}_{lm} - \theta_{lm}^{shift})\\ \cos(\hat{\delta}_{lm} - \theta_{lm}^{shift}) & -\sin(\hat{\delta}_{lm} - \theta_{lm}^{shift})\end{bmatrix}\begin{bmatrix}\alpha_{lm} & \beta_{lm}\\ -\beta_{lm} & \alpha_{lm}\end{bmatrix}\right)$$

and, for notational convenience, $\hat{\delta}_{lm} = \delta_{lm} + \psi$.

B. Parallel Lines

In the original QC relaxation (5), the power flow equations for parallel lines between buses l and m shared the same envelopes, $\langle\cos(\theta_{lm})\rangle^C$ and $\langle\sin(\theta_{lm})\rangle^S$. In the RQC relaxation (16), the arguments of the trigonometric terms for parallel lines can differ due to the inclusion of the δ_{lm} terms. Rather than defining separate envelopes, we derive a linear relationship between the trigonometric terms for parallel lines. Let δ_{lm_1}, δ_{lm_2} and $\theta_{lm_1}^{shift}$, $\theta_{lm_2}^{shift}$ be the admittance angles and phase shifts, respectively, for two parallel lines between buses l and m. Applying the angle sum identity yields

$$\begin{bmatrix}\sin(\sigma_{lm_1} - \theta_{lm})\\ \cos(\sigma_{lm_1} - \theta_{lm})\\ \sin(\sigma_{lm_2} - \theta_{lm})\\ \cos(\sigma_{lm_2} - \theta_{lm})\end{bmatrix} = \begin{bmatrix}\sin(\sigma_{lm_1}) & -\cos(\sigma_{lm_1})\\ \cos(\sigma_{lm_1}) & \sin(\sigma_{lm_1})\\ \sin(\sigma_{lm_2}) & -\cos(\sigma_{lm_2})\\ \cos(\sigma_{lm_2}) & \sin(\sigma_{lm_2})\end{bmatrix}\begin{bmatrix}\cos(\theta_{lm})\\ \sin(\theta_{lm})\end{bmatrix}, \tag{26}$$

where, for notational convenience, $\sigma_{lm_1} = \delta_{lm_1} + \theta_{lm_1}^{shift} + \psi$ and $\sigma_{lm_2} = \delta_{lm_2} + \theta_{lm_2}^{shift} + \psi$. Rearranging (26) to eliminate $\cos(\theta_{lm})$ and $\sin(\theta_{lm})$ yields the desired linear relationship:

$$\begin{bmatrix}\sin(\theta_{lm} - \sigma_{lm_2})\\ \cos(\theta_{lm} - \sigma_{lm_2})\end{bmatrix} = \\ \begin{bmatrix}\cos(\sigma_{lm_1} - \sigma_{lm_2}) & \sin(\sigma_{lm_1} - \sigma_{lm_2})\\ -\sin(\sigma_{lm_1} - \sigma_{lm_2}) & \cos(\sigma_{lm_1} - \sigma_{lm_2})\end{bmatrix}\begin{bmatrix}\sin(\theta_{lm} - \sigma_{lm_1})\\ \cos(\theta_{lm} - \sigma_{lm_1})\end{bmatrix}. \tag{27}$$

Since the matrix in (27) is invertible, this relationship is always well defined.

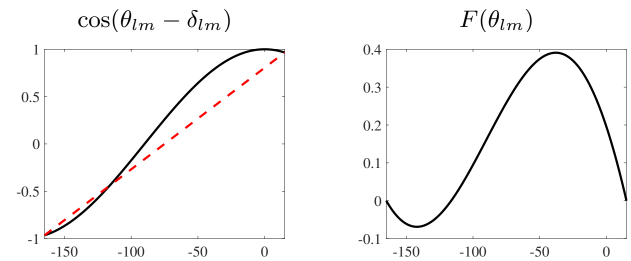
C. Tighter Boundaries for Certain Trigonometric Envelopes

This appendix formalizes and proves a statement in Section V-A regarding the tightness of the trigonometric envelopes in the original formulation of the QC relaxation (5) and the proposed polar admittance QC formulation (16).

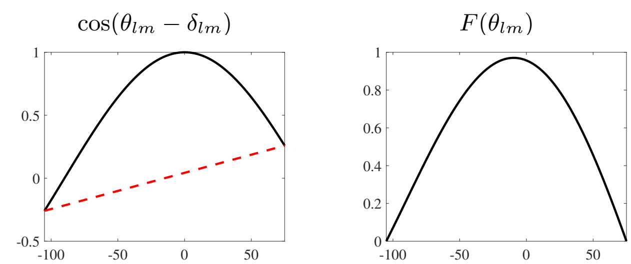
To assist the derivations in this appendix, we define a function $F(\theta_{lm})$ which represents the difference between the trigonometric function $\cos(\theta_{lm} - \delta_{lm})$ itself and the line which connects the endpoints of $\cos(\theta_{lm} - \delta_{lm})$ at θ_{lm}^{min} and θ_{lm}^{max}:

$$F(\theta_{lm}) = \cos(\theta_{lm} - \delta_{lm}) - \cos(\theta_{lm}^{max} - \delta_{lm}) \\ - \frac{\cos(\theta_{lm}^{max} - \delta_{lm}) - \cos(\theta_{lm}^{min} - \delta_{lm})}{\theta_{lm}^{max} - \theta_{lm}^{min}}\left(\theta_{lm} - \theta_{lm}^{max}\right) \tag{28}$$

Fig. 6 shows illustrative examples of the function $Y_{lm}\cos(\theta_{lm} - \delta_{lm})$ (black curve) and the line connecting the endpoints of this function at θ_{lm}^{min} and θ_{lm}^{max} (dashed red line) on the left, with corresponding visualizations of the function $F(\theta_{lm})$ itself on the right.



(a) $165^\circ \leqslant \theta_{lm} - \delta_{lm} \leqslant 15^\circ$



(b) $165^\circ \leqslant \theta_{lm} - \delta_{lm} \leqslant 15^\circ$

Figure 6. The left figures show visualizations of the function $\cos(\theta_{lm} - \delta_{lm})$ (black curve) and the line connecting the endpoints of this function at θ_{lm}^{min} and θ_{lm}^{max} (dashed red line) for different values of δ_{lm}, θ_{lm}^{min}, and θ_{lm}^{max}. The right figures show the corresponding function $F(\theta_{lm})$.

The derivative of $F(\theta_{lm})$ is

$$\frac{dF(\theta_{lm})}{d\theta_{lm}} = -\sin(\theta_{lm} - \delta_{lm}) \\ - \frac{\cos(\theta_{lm}^{max} - \delta_{lm}) - \cos(\theta_{lm}^{min} - \delta_{lm})}{\theta_{lm}^{max} - \theta_{lm}^{min}}. \tag{29}$$

A key quantity in the following proposition is the set of zeros of the derivative of $F(\theta_{lm})$, i.e., the set of solutions to $\frac{dF(\theta_{lm})}{d\theta_{lm}} = 0$. This set, which we denote by $\mathcal{Z}_{\theta_{lm}^{min},\theta_{lm}^{max},\delta_{lm}}$

where the subscripts indicate that the set is parameterized by θ_{lm}^{min}, θ_{lm}^{max}, and δ_{lm}, is

$$\mathcal{Z}_{\theta_{lm}^{min},\theta_{lm}^{max},\delta_{lm}} = \Bigg\{(-1)^{\kappa}\arcsin\left(\frac{\cos(\theta_{lm}^{min}-\delta_{lm})-\cos(\theta_{lm}^{max}-\delta_{lm})}{\left(\theta_{lm}^{max}-\theta_{lm}^{min}\right)}\right)+\pi\kappa,\quad \kappa=\ldots,-3,-2,-1,0,1,2,3,\ldots\Bigg\}.$$

Finally, we let $|\cdot|$ denote the cardinality of a set.

Using these definitions, we next state and prove the following proposition.

Proposition 1. The lower boundary of the envelope $Y_{lm}\left\langle\cos(\theta_{lm}-\delta_{lm})\right\rangle^C$ is at least as tight as the lower boundary of the envelope $g_{lm}\left\langle\cos(\theta_{lm})\right\rangle^C + b_{lm}\left\langle\sin(\theta_{lm})\right\rangle^S$ if θ_{lm}^{min}, θ_{lm}^{max}, and δ_{lm} satisfy both of the following conditions:

$$\left|\mathcal{Z}_{\theta_{lm}^{min},\theta_{lm}^{max},\delta_{lm}}\bigcap\left\{\theta_{lm}^{min}<\theta_{lm}<\theta_{lm}^{max}\right\}\right| = 1, \tag{30a}$$

$$F\left(\left(\theta_{lm}^{max}+\theta_{lm}^{min}\right)/2\right) > 0. \tag{30b}$$

Moreover, the upper boundary of the envelope $Y_{lm}\left\langle\cos(\theta_{lm}-\delta_{lm})\right\rangle^C$ is at least as tight as the upper boundary of the envelope $g_{lm}\left\langle\cos(\theta_{lm})\right\rangle^C + b_{lm}\left\langle\sin(\theta_{lm})\right\rangle^S$ if θ_{lm}^{min}, θ_{lm}^{max}, and δ_{lm} satisfy both (30a) and the condition

$$F\left(\left(\theta_{lm}^{max}+\theta_{lm}^{min}\right)/2\right) < 0. \tag{31}$$

Proof. The proof is based on the following observation: if the line connecting the points $(\theta_{lm}^{min}, \cos(\theta_{lm}^{min}-\delta_{lm}))$ and $(\theta_{lm}^{max}, \cos(\theta_{lm}^{max}-\delta_{lm}))$ (i.e., the dashed red line in Fig. 6) does not intersect the function $\cos(\theta_{lm}-\delta_{lm})$ itself within the range $\theta_{lm}^{min} < \theta_{lm} < \theta_{lm}^{max}$, then this line is either the lower boundary or upper boundary of the tighest convex envelope for the function $\cos(\theta_{lm}-\delta_{lm})$ within this range. (For instance, the dashed red line in Fig. 6b is the lower boundary of the tighest envelope for $\cos(\theta_{lm}-\delta_{lm})$ within the range $-165^\circ \leqslant \theta_{lm} \leqslant 15^\circ$.) In this case, the line is the tightest lower (upper) boundary if the function $\cos(\theta_{lm}-\delta_{lm})$ is above (below) the line for any point between θ_{lm}^{min} and θ_{lm}^{max} (e.g., the midpoint $(\theta_{lm}^{min}+\theta_{lm}^{max})/2$, which is used in (30b) and (31)).

Observe that the line connecting the points $(\theta_{lm}^{min}, \cos(\theta_{lm}^{min}-\delta_{lm}))$ and $(\theta_{lm}^{max}, \cos(\theta_{lm}^{max}-\delta_{lm}))$ does not intersect the function $\cos(\theta_{lm}-\delta_{lm})$ between θ_{lm}^{min} and θ_{lm}^{max} if and only if $F(\theta_{lm})$ is non-zero for all $\theta_{lm}^{min} < \theta_{lm} < \theta_{lm}^{max}$. We next argue that this is implied by (30a).

The condition (30a) is equivalent to the existence of one critical point θ_{lm}^* of the function $F(\theta_{lm})$. (i.e., the derivative of $F(\theta)$ has a single zero, θ_{lm}^*, in the range $\theta_{lm}^{min} < \theta_{lm} < \theta_{lm}^{max}$. Since $F(\theta_{lm})$ is continuous and $F(\theta_{lm}^{min}) = F(\theta_{lm}^{max}) = 0$, the critical point θ_{lm}^* must either correspond to a minimum or maximum of $F(\theta_{lm})$. Since the function $F(\theta_{lm})$ is zero at the endpoints θ_{lm}^{min} and θ_{lm}^{max}, having a single minimum or maximum in the range $\theta_{lm}^{min} < \theta_{lm} < \theta_{lm}^{max}$ implies that $F(\theta_{lm}) \neq 0$ within this range.

To complete the conditions in the proposition, (30b) and (31) determine whether the line connecting the points $(\theta_{lm}^{min}, \cos(\theta_{lm}^{min}-\delta_{lm}))$ and $(\theta_{lm}^{max}, \cos(\theta_{lm}^{max}-\delta_{lm}))$ is above or below the function $\cos(\theta_{lm}-\delta_{lm})$ by evaluating the function $F(\theta_{lm})$ at an arbitrary point between θ_{lm}^{min} and θ_{lm}^{max}, here selected to be the midpoint $\left(\theta_{lm}^{min}+\theta_{lm}^{max}\right)/2$.

Since multiplication by Y_{lm} only rescales (but does not otherwise change) the envelope $\left\langle\cos(\theta_{lm}-\delta_{lm})\right\rangle^C$, the arguments above trivially extend to $Y_{lm}\left\langle\cos(\theta_{lm}-\delta_{lm})\right\rangle^C$. Moreover, since $Y_{lm}\cos(\theta_{lm}-\delta_{lm}) = g_{lm}\cos(\theta_{lm})+b_{lm}\sin(\theta_{lm})$, the envelope $g_{lm}\left\langle\cos(\theta_{lm})\right\rangle^C + b_{lm}\left\langle\sin(\theta_{lm})\right\rangle^S$ cannot be tighter than the tightest possible envelope for $Y_{lm}\cos(\theta_{lm}-\delta_{lm})$. Since the boundaries of $Y_{lm}\left\langle\cos(\theta_{lm}-\delta_{lm})\right\rangle^C$ considered in the proof form portions of the tightest possible convex envelope for $Y_{lm}\cos(\theta_{lm}-\delta_{lm})$, they are at least as tight as the corresponding boundaries of the envelope $g_{lm}\left\langle\cos(\theta_{lm})\right\rangle^C + b_{lm}\left\langle\sin(\theta_{lm})\right\rangle^S$. Furthermore, the example envelopes in Fig. 2 show that the corresponding boundaries of $Y_{lm}\left\langle\cos(\theta_{lm}-\delta_{lm})\right\rangle^C$ are strictly tighter than those of $g_{lm}\left\langle\cos(\theta_{lm})\right\rangle^C + b_{lm}\left\langle\sin(\theta_{lm})\right\rangle^S$ for some values of δ_{lm}, θ_{lm}^{min}, and θ_{lm}^{max}.

□

We finally note that values of θ_{lm}^{min}, θ_{lm}^{max}, and δ_{lm} such that $\max(-90^\circ, -90^\circ+\delta_{lm}) \leqslant \theta_{lm}^{min} < \theta_{lm}^{max} \leqslant \min(90^\circ, 90^\circ+\delta_{lm})$ satisfy (30). Thus, the trigonometric envelopes corresponding to the polar admittance representation have lower boundaries that are at least as tight as those in the original QC relaxation for many typical values of θ_{lm}^{min}, θ_{lm}^{max}, and δ_{lm}.

D. Expressions for the Vertices of the Polytope Associated with the Trilinear Products

This appendix presents expressions for the vertices of the polytope consisting of the black dashed lines in Fig. 3. To compute the coordinates of these vertices (black dots in Fig. 7), we intersect the edges of the receiving end polytope, which is formed by the upper and lower bounds on the receiving end quantities, $\overline{\tilde{S}}_{lm}^{(r)}$, $\overline{\tilde{C}}_{lm}^{(r)}$ and $\underline{\tilde{S}}_{lm}^{(r)}$, $\underline{\tilde{C}}_{lm}^{(r)}$, respectively, with the edges of the sending end polytope, which is formed by the upper and lower bounds on the sending end quantities $\overline{\tilde{S}}_{lm}^{(s)}$, $\overline{\tilde{C}}_{lm}^{(s)}$ and $\underline{\tilde{S}}_{lm}^{(s)}$, $\underline{\tilde{C}}_{lm}^{(s)}$, respectively.

When written in terms of the sending end quantities $\tilde{S}_{lm}^{(s)}$ and $\tilde{C}_{lm}^{(s)}$, the coordinates for the upper and lower bounds on the receiving end quantities are functions of ψ. To write the coordinates of the vertices as functions of ψ, consider the line segments labeled in Fig. 7. The yellow and purple polytopes in this figure represent the bounds on the sending and receiving end quantities, respectively. Table II describes the relevant intersections of the line segments that form these polytopes. For the ranges of ψ in the first column of Table II, the remaining columns indicate the line segments whose intersections form the corresponding vertices. The coordinates of these intersections are given in Table III. As an example for $-45^\circ \leqslant \psi \leqslant 0^\circ$, the $A'D'$ line segment in Fig. 7 should intersect line segments AB and AD. The coordinates of these intersections are given in rows 13 and 16 of Table III.

References

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[2] D. Bienstock and A. Verma, "Strong NP-hardness of AC Power Flows Feasibility," *Oper. Res. Lett.*, vol. 47, no. 6, pp. 494–501, 2019.

Table II
LINE SEGMENT INTERSECTIONS CORRESPONDING TO FIG. 7

ψ (degrees)	$A'B'$	$B'C'$	$C'D'$	$A'D'$
$-45 \leqslant \psi \leqslant 0$	AB & BC	BC & CD	CD & AD	AB & AD
$-90 \leqslant \psi \leqslant -45$	BC & CD	CD & AD	AB & AD	AB & BC
$-135 \leqslant \psi \leqslant -90$	CD & AD	AB & AD	AB & BC	BC & CD
$-180 \leqslant \psi \leqslant -135$	AB & AD	AB & BC	BC & CD	CD & AD
$0 \leqslant \psi \leqslant 45$	AD & AB	AB & BC	BC & CD	CD & AD
$45 \leqslant \psi \leqslant 90$	CD & AD	AD & AB	AB & BC	BC & CD
$90 \leqslant \psi \leqslant 135$	BC & CD	CD & AD	AD & AB	AB & BC
$135 \leqslant \psi \leqslant 180$	AB & BC	BC & CD	CD & AD	AD & AB

Table III
COORDINATES OF THE LINE SEGMENT INTERSECTIONS IN TABLE II.

Line Segments	Coordinates of the Intersection Point
$A'B'$ & AB	$\left(\frac{\alpha_{lm}}{\beta_{lm}}\overline{\tilde{S}}_{lm}^{(s)} - \beta_{lm}\overline{\tilde{S}}_{lm}^{(r)}) - \frac{\alpha_{lm}^2\overline{\tilde{S}}_{lm}^{(r)})}{\beta_{lm}},\ \overline{\tilde{S}}_{lm}^{(s)}\right)$
$A'B'$ & BC	$\left(\underline{\tilde{C}}_{lm}^{(s)},\ \frac{\beta_{lm}\underline{\tilde{C}}_{lm}^{(s)})}{\alpha_{lm}} + \frac{\beta_{lm}^2\overline{\tilde{S}}_{lm}^{(r)})}{\alpha_{lm}} + \alpha_{lm}\overline{\tilde{S}}_{lm}^{(r)}\right)$
$A'B'$ & CD	$\left(\frac{\alpha_{lm}}{\beta_{lm}}\underline{\tilde{S}}_{lm}^{(s)} - \beta_{lm}\overline{\tilde{S}}_{lm}^{(r)}) - \frac{\alpha_{lm}^2\overline{\tilde{S}}_{lm}^{(r)})}{\beta_{lm}},\ \underline{\tilde{S}}_{lm}^{(s)}\right)$
$A'B'$ & AD	$\left(\overline{\tilde{C}}_{lm}^{(s)},\ \frac{\beta_{lm}\overline{\tilde{C}}_{lm}^{(s)})}{\alpha_{lm}} + \frac{\beta_{lm}^2\overline{\tilde{S}}_{lm}^{(r)})}{\alpha_{lm}} + \alpha_{lm}\overline{\tilde{S}}_{lm}^{(r)}\right)$
$B'C'$ & BC	$\left(\underline{\tilde{C}}_{lm}^{(s)},\ -\frac{\alpha_{lm}\underline{\tilde{C}}_{lm}^{(s)})}{\beta_{lm}} + \frac{\alpha_{lm}^2\underline{\tilde{C}}_{lm}^{(r)})}{\beta_{lm}} + \beta_{lm}\underline{\tilde{C}}_{lm}^{(r)}\right)$
$B'C'$ & CD	$\left(-\frac{\beta_{lm}}{\alpha_{lm}}\underline{\tilde{S}}_{lm}^{(s)} + \alpha_{lm}\underline{\tilde{C}}_{lm}^{(r)}) + \frac{\beta_{lm}^2\underline{\tilde{C}}_{lm}^{(r)})}{\alpha_{lm}},\ \underline{\tilde{S}}_{lm}^{(s)}\right)$
$B'C'$ & AB	$\left(-\frac{\beta_{lm}}{\alpha_{lm}}\overline{\tilde{S}}_{lm}^{(s)} + \alpha_{lm}\underline{\tilde{C}}_{lm}^{(r)}) + \frac{\beta_{lm}^2\underline{\tilde{C}}_{lm}^{(r)})}{\alpha_{lm}},\ \overline{\tilde{S}}_{lm}^{(s)}\right)$
$B'C'$ & AD	$\left(\overline{\tilde{C}}_{lm}^{(s)},\ -\frac{\alpha_{lm}\overline{\tilde{C}}_{lm}^{(s)})}{\beta_{lm}} + \frac{\alpha_{lm}^2\underline{\tilde{C}}_{lm}^{(r)})}{\beta_{lm}} + \beta_{lm}\underline{\tilde{C}}_{lm}^{(r)}\right)$
$C'D'$ & AB	$\left(\frac{\alpha_{lm}}{\beta_{lm}}\overline{\tilde{S}}_{lm}^{(s)} - \beta_{lm}\underline{\tilde{S}}_{lm}^{(r)}) - \frac{\alpha_{lm}^2\underline{\tilde{S}}_{lm}^{(r)})}{\beta_{lm}},\ \overline{\tilde{S}}_{lm}^{(s)}\right)$
$C'D'$ & BC	$\left(\underline{\tilde{C}}_{lm}^{(s)},\ \frac{\beta_{lm}\underline{\tilde{C}}_{lm}^{(s)})}{\alpha_{lm}} + \frac{\beta_{lm}^2\underline{\tilde{S}}_{lm}^{(r)})}{\alpha_{lm}} + \alpha_{lm}\underline{\tilde{S}}_{lm}^{(r)}\right)$
$C'D'$ & CD	$\left(\frac{\alpha_{lm}}{\beta_{lm}}\underline{\tilde{S}}_{lm}^{(s)} - \beta_{lm}\underline{\tilde{S}}_{lm}^{(r)}) - \frac{\alpha_{lm}^2\underline{\tilde{S}}_{lm}^{(r)})}{\beta_{lm}},\ \underline{\tilde{S}}_{lm}^{(s)}\right)$
$C'D'$ & AD	$\left(\overline{\tilde{C}}_{lm}^{(s)},\ \frac{\beta_{lm}\overline{\tilde{C}}_{lm}^{(s)})}{\alpha_{lm}} + \frac{\beta_{lm}^2\underline{\tilde{S}}_{lm}^{(r)})}{\alpha_{lm}} + \alpha_{lm}\underline{\tilde{S}}_{lm}^{(r)}\right)$
$A'D'$ & AB	$\left(-\frac{\beta_{lm}}{\alpha_{lm}}\overline{\tilde{S}}_{lm}^{(s)} + \alpha_{lm}\overline{\tilde{C}}_{lm}^{(r)}) + \frac{\beta_{lm}^2\overline{\tilde{C}}_{lm}^{(r)})}{\alpha_{lm}},\ \overline{\tilde{S}}_{lm}^{(s)}\right)$
$A'D'$ & BC	$\left(\underline{\tilde{C}}_{lm}^{(s)},\ -\frac{\alpha_{lm}\underline{\tilde{C}}_{lm}^{(s)})}{\beta_{lm}} + \frac{\alpha_{lm}^2\overline{\tilde{C}}_{lm}^{(r)})}{\beta_{lm}} + \beta_{lm}\overline{\tilde{C}}_{lm}^{(r)}\right)$
$A'D'$ & CD	$\left(-\frac{\beta_{lm}}{\alpha_{lm}}\underline{\tilde{S}}_{lm}^{(s)} + \alpha_{lm}\overline{\tilde{C}}_{lm}^{(r)}) + \frac{\beta_{lm}^2\overline{\tilde{C}}_{lm}^{(r)})}{\alpha_{lm}},\ \underline{\tilde{S}}_{lm}^{(s)}\right)$
$A'D'$ & AD	$\left(\overline{\tilde{C}}_{lm}^{(s)},\ -\frac{\alpha_{lm}\overline{\tilde{C}}_{lm}^{(s)})}{\beta_{lm}} + \frac{\alpha_{lm}^2\overline{\tilde{C}}_{lm}^{(r)})}{\beta_{lm}} + \beta_{lm}\overline{\tilde{C}}_{lm}^{(r)}\right)$

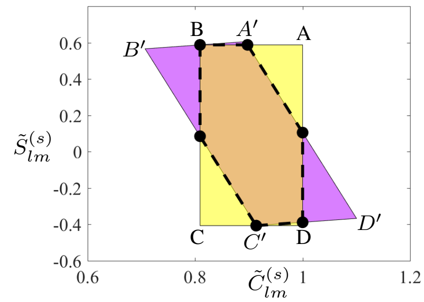

Figure 7. A projection of the four-dimensional polytope associated with the trilinear products between the voltage magnitudes and the trigonometric functions, expressed in terms of the sending end variables $\tilde{S}_{lm}^{(s)}$ and $\tilde{C}_{lm}^{(s)}$ representing $\cos(\theta_{lm} - \delta_{lm} - \psi)$ and $\sin(\theta_{lm} - \delta_{lm} - \psi)$. The polytope formed by intersecting the sending end polytope (ABCD) and receiving end polytope ($A'B'C'D'$) is outlined with the dashed black lines and has vertices shown by the black dots.

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