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Analytic Loss Minimization: A Proof
Paul Cuffe, Ioannis Dassios, Andrew Keane

Abstract—Loss minimizing generator dispatch profiles for power systems are usually derived using optimization techniques. However, some authors have noted that a system’s $K_{GL}$ matrix can be used to analytically determine a loss minimizing dispatch. This letter draws on recent research on the characterization of transmission system losses to demonstrate how the $K_{GL}$ matrix achieves this. A new proof of the observed zero row summation property of the $Y_{GGM}$ matrix is provided to this end.

I. INTRODUCTION

Various works [1], [2] have noted that the $K_{GL}$ matrix allows the direct calculation of a generator dispatch profile that appears to minimize active power losses. The literature offers scant explanation for how this result is achieved. The recent work of Abdelkader et al. [3], [4] offers useful insight here. Crucially, [4] shows how network losses can be separated into three distinct components. One of these loss components arises solely because of mismatched generator voltages, which cause circulating currents to flow through the system [3]. This letter demonstrates how the $K_{GL}$ matrix can give an ideal generator dispatch profile which equalizes generator complex voltages, so no circulating currents will flow and this loss component is nullified.

II. SEPARATION OF SYSTEM LOSSES

A. Partitioning

The $Y_{bus}$ is reordered, per [5], such that the $m$ generator buses (G subscript) and $n$ load buses (L) are grouped together:

$$
[I_G | I_L] = [Y_{GG} Y_{GL} | Y_{LG} Y_{LL}] [V_G | V_L]
$$

(1)

$I_G$ and $I_L$ are complex-valued vectors representing the nodal currents at generator and load buses, respectively, while $V_G$ and $V_L$ are corresponding complex nodal voltages. Manipulation of (1) gives:

$$
[V_L | I_L] = [Z_{LL} F_{LG} | K_{GL} Y_{GGM}] [I_G | V_G]
$$

(2)

Where:

$$
Y_{GGM} = Y_{GG} - Y_{GL}Z_{LL}Y_{LG}
$$

(3)

$$
F_{LG} = -Z_{LL}Y_{LG} = -K_{GL}
$$

(4)

B. Loss Characterization

Per [4], the network loss is calculated as the difference between aggregate powers on the generation and load sides of the network. To find the total power generated, use the $I_G$ expression from (2), left-multiplied by $V_G$ to give a single complex value:

$$
S_G^{Tot} = V_G^T I_G = V_G^T Y_{GGM} V_G^* + V_G^T Y_{GL} Z_{LL} I_L
$$

(5)

Equivalently, multiplying the $V_L$ expression from (2) by $I_L$ expresses the total load power consumed as a complex number:

$$
S_L^{Tot} = V_L^T I_L = I_L^T Z_{LL} I_L - V_G^T Y_{LG} Z_{LL} I_L
$$

(6)

Given their opposite signs, summing these expressions gives the total system loss:

$$
S_{Loss}^{Tot} = S_G^{Tot} + S_L^{Tot}
$$

(7)

Which equals:

$$
V_G^T Y_{GGM} V_G^* + V_G^T (Y_{GL} Z_{LL} - Y_{LG} Z_{LL}) I_L + I_L^T Z_{LL} I_L
$$

(8)

The system losses naturally separate themselves into three distinct components. The first term is the circulating current loss, and it depends solely on generator voltages. The middle component, the mismatch loss, will only arise when branch $X/R$ ratios are heterogeneous, and will in any case generally be small and imaginary [4]. The last component is the load current loss, which cannot be affected by the system operator, being a pure consequence of system topology and load currents. As will be shown, the $Y_{GGM}$ matrix has the property that its rows sum to zero, and so its product can be brought to zero by right-multiplying it by a vector whose elements are homogeneous. Thus, if generator voltages are uniform, there will be no excess circulating current loss, and the active power losses will reduce to the irreducible component which arises from serving load currents.

III. ZERO ROW SUMMATION OF $Y_{GGM}$

Theorem If every row of the $Y_{bus}$ matrix sums to zero and $detY_{LL} \neq 0$, then every row of $Y_{GGM}$ sums to zero. If every row of the $Y_{bus}$ matrix sums approximately to zero, or if it sums to zero but $detY_{LL}=0$, then every row of the matrix $Y_{GGM}$ sums approximately to zero.

Proof The matrix $Y_{GGM}$ can be written as

$$
Y_{GGM} = Y_{GG} + Y_{GL} F_{LG},
$$

(9)

since $F_{LG} = -Z_{LL} Y_{LG}$. Where

$$
Z_{LL} = \begin{cases} 
Y_{LL}^{-1}, & det(Y_{LL}) \neq 0 \\
Y_{LL}^{†}, & det(Y_{LL}) = 0 
\end{cases}
$$

(10)

For ease of notation set $Y_{GG} = [a_{ij}]_{i=1,2,...,m}$, and similarly:

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\[ YGL = [b_{ij}]_{m \times n} \quad F_{LG} = [c_{ij}]_{n \times m} \]
\[ YGL F_{LG} = [d_{ij}]_{m \times m} \quad Y_{GGM} = [g_{ij}]_{m \times m} \]

By substituting the previous expressions into (9), for every row \( i = 1, 2, \ldots, m \) we have:
\[ \sum_{j=1}^{m} g_{ij} = \sum_{j=1}^{m} a_{ij} + \sum_{j=1}^{m} d_{ij}. \]  
(12)

In addition:
\[ d_{ij} = \sum_{k=1}^{n} b_{ik} c_{k1} \]
\[ d_{im} = \sum_{k=1}^{n} b_{ik} c_{km}. \]

By taking the sum of the above equalities, \( \forall i = 1, 2, \ldots, n \) we arrive at:
\[ \sum_{j=1}^{m} d_{ij} = \sum_{j=1}^{m} \sum_{k=1}^{n} b_{ik} c_{kj}. \]  
(13)

Disregarding shunt elements, the \( Y_{bus} \) is a weighted Laplacian matrix [6], and so each of its rows will sum to zero. Accordingly:
\[ \sum_{j=1}^{m} a_{ij} + \sum_{j=1}^{m} b_{ij} = 0, \quad \forall i = 1, 2, \ldots, m. \]  
(14)

By replacing (13) into (12) we get:
\[ \sum_{j=1}^{m} g_{ij} = \sum_{j=1}^{m} a_{ij} + \sum_{j=1}^{m} b_{ik} c_{kj} \]
and using (14):
\[ \sum_{j=1}^{m} g_{ij} = -\sum_{k=1}^{n} b_{ik} + \sum_{j=1}^{m} \sum_{k=1}^{n} b_{ik} c_{kj}. \]  
(15)

which equals:
\[ -\sum_{k=1}^{n} b_{ik} + \sum_{k=1}^{n} b_{ik} \left( \sum_{j=1}^{m} c_{kj} \right). \]  
(16)

which equals:
\[ \sum_{k=1}^{n} \left[ -b_{ik} + b_{ik} \left( \sum_{j=1}^{m} c_{kj} \right) \right]. \]  
(17)

or, equivalently:
\[ \sum_{j=1}^{m} g_{ij} = \sum_{k=1}^{n} \left[ \sum_{j=1}^{m} c_{kj} \right] b_{ik}. \]  
(18)

As the authors have shown in [7], if \( \det(Y_{LL}) \neq 0 \), then every row of \( F_{LG} \) sums to one, i.e. \( \sum_{j=1}^{m} c_{kj} = 1, \forall k = 1, 2, \ldots, n. \)
Thus, from (19), \( \sum_{j=1}^{m} g_{ij} = 0 \), and so every row of \( Y_{GGM} \) sums to zero. Similarly, if \( \det(Y_{LL}) = 0 \), then every row of \( F_{LG} \) sums approximately to one, i.e. \( \sum_{j=1}^{m} c_{kj} \approx 1, \forall k = 1, 2, \ldots, n. \)
Thus, from (19), \( \sum_{j=1}^{m} g_{ij} \approx 0 \), and so every row of \( Y_{GGM} \) sums approximately to zero.

With equivalent steps if every row of \( Y_{bus} \) sums approximately to zero then every row of \( Y_{GGM} \) sums approximately to zero.

IV. Minimizing Losses

Taken together, (8) and the newly demonstrated zero row sum property of \( Y_{GGM} \), and accordingly, its conjugate, imply that losses are minimized when generator voltages are homogeneous. As such, and disregarding machine limits, an optimal dispatch can be directly calculated by setting all \( V_G \) equal to the slack value, \( 1 \leq 0 \), and solving the resulting loadflow problem by the familiar iterative techniques. More insightfully, though, one can use the previously derived block matrix equations to see how this optimal dispatch relates to load current demands. Recall from (2):
\[ I_G = K_G L + Y_{GGM} V_G \]
(20)

Minimum loss conditions implies that \( V_G \) will be homogeneous, and so the second term of (20) reduces to zero. Therefore, we can infer the unconstrained generator dispatch that would realise this flat voltage profile:
\[ I_G = K_G L L = S^{Opt}_G \]
(21)

The equivalence of \( I_G \) and \( S_G \) in these conditions is assured because generator voltages are all at the slack value. Assuming that load voltages are close to this value, we can further state that \( S_L \approx I_L \). This interpretation of (21) in power terms shows how to use the \( K_G L \) and \( I_L \) to calculate an unconstrained generator dispatch that precludes circulating current losses. This explains the technique presented without proof in [1].

V. Concluding Example

Table I shows three possible dispatches for the 30 bus system. For context, the second row shows the dispatch achieved using the loss-minimizing optimization of [8]. The \( F_G^{Opt} \) dispatch achieves slightly lower losses than this. The largest row sum of this system’s \( Y_{GGM} \) is \((-0.0028+0.0752j)\) i.e close to zero.

<table>
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<tr>
<th></th>
<th>G1</th>
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<th>G5</th>
<th>G8</th>
<th>G11</th>
<th>G13</th>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<td>76.82</td>
<td>55.62</td>
<td>52.98</td>
<td>39.17</td>
<td>285.57</td>
</tr>
<tr>
<td>( F_G^{Opt} )</td>
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<td>40.08</td>
<td>105.89</td>
<td>70.27</td>
<td>19.16</td>
<td>35.43</td>
<td>285.49</td>
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REFERENCES