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*Research Article*

# Sufficient Condition for the Parallel Flow Problem of Electromagnetic Loop Networks

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Electromagnetic loop networks (EMLNs) are pervasive in power networks. Their major characteristic is parallel flow. EMLNs with substantial parallel flow are considered to have a parallel flow problem. There is currently a serious disagreement about whether EMLNs have a parallel flow problem, which has resulted in different configurations of national grids. Therefore, this paper proposes a general model of EMLNs and derives the parallel current function, which formulates parallel flow, from the network equations of both the high and low voltage sides of an EMLN. Accordingly, the high and low voltage sides of an EMLN are equivalent to two sets of parallel identical multi-transmission lines. Finally, this paper considers operating margins and derives the sufficient condition under which parallel flow can be ignored. The sufficient condition not only determines whether an EMLN has a parallel flow problem but also reveals simple approaches to visually diminishing parallel flow. If the EMLN satisfies the sufficient condition, parallel flow can be ignored; otherwise, the EMLN needs to operate in a restricted way or to adopt open loop planning.

## 1. Introduction

An electromagnetic loop network (EMLN) is a loop configuration of transmission lines with different voltage classes in a power network. Many EMLNs exist if the power transmission network consists of lines with two major voltage classes. Sometimes, high voltage and long distance transmission lines are required to operate in a parallel configuration with a low voltage class network, which is actually an EMLN. In addition, EMLNs exist in distribution networks, such as the isolated substations loop network in [1–3] and certain MV mesh distribution network in [4]. Therefore, EMLN research has broad practical significance.

A major characteristic of EMLNs is that the power flow on the high voltage side influences the power flow on the low voltage side. This phenomenon is hereinafter referred to as the parallel flow phenomenon. Due to the parallel configuration between the high and low voltage side networks, the power flow on the high voltage side network generates additional flow, designated as transporting flow, through the low voltage side network [5]. The transporting flow is analogous to the loop flow in [6]. If the power flow on the high voltage side network is aggravated, the transporting flow increases and deteriorates the operating conditions of the low voltage side network; therefore, the transmission capacity of the high voltage side of an EMLN is limited [7]. Furthermore, if the load demand increases, the lines on the low voltage side of the EMLN may be unable to maintain sufficient margins because of parallel flow. An EMLN is considered to have a parallel flow problem if the safe operation of the EMLN has to account for parallel flow.

Some researchers believe that most EMLNs have a parallel flow problem. They ascribe severe parallel flow to the large difference between the capacities of the lines on the high and low voltage side networks. Moreover, if a line on the high voltage side network is cut off, a large amount power may flow into the lines on the low voltage side network, significantly deteriorating their operating conditions. Most blackouts in history are related to the EMLN configuration [8–14], so these researchers assert that EMLNs should be avoided if possible. For example, the state grid of China prefers to open the EMLN in a controlled and planned manner once the EMLN satisfies some open loop conditions [15]. For this purpose, many Chinese researchers have qualitatively described the potential hazards of EMLNs [16] and have developed substantial approaches for opening EMLNs [17].

In contrast, other researchers believe that the parallel flow of EMLNs does not constitute a problem. They think that if the power flow is sufficiently small, EMLN parallel flow does not threaten the operation of the power system; at a heavier power flow circumstance, although parallel flow exists, it is the peak load demand or another critical factor that pushes the power system towards critical conditions [18, 19]. A power network without an EMLN cannot handle heavy power flow conditions as well as one with an EMLN. Moreover, contingency analysis is applicable to power networks regardless of the presence on EMLNs [20–24]. Therefore, these researchers believe that it is not necessary to specifically extract and study EMLNs or to deliberately avoid them. For example, despite the many EMLNs in the power transmission network in Germany [25], satisfactory operating conditions are maintained. Moreover, the problems of EMLNs have not drawn much attention, at least in English-language academic journals.

Do EMLNs have a parallel flow problem? There is currently no sufficient rational and objective approach to answer this question. The researchers who hold affirmative opinions base their conclusions on equivalent models and the qualitative drawbacks of EMLNs [16, 26]; however, this approach does not prove that the parallel flow of an EMLN constitutes a problem. The researchers who hold negative opinions ascribe the outages associated with EMLNs to other factors [27, 28]. Meanwhile, they neglect the objective reality that parallel flow in an EMLN is likely to deteriorate the operating conditions of the low voltage side network.

This paper formulates the parallel flow of EMLNs and derives the sufficient condition for the EMLN parallel flow problem. First, according to the network equations of the high and low voltage side networks, the current components that are generated by the high voltage side network are extracted from the branches of low voltage side network. These components are expressed as a system of linear functions with respect to the branch currents on the high voltage side network. Second, the system of linear functions is utilized to make the high and low voltage sides of the EMLN equivalent to two sets of parallel identical multi-transmission lines. Third, according to the margins of the branches, the sufficient condition, with respect to the transmission lines, to prevent the EMLN parallel flow problem is induced. Finally, the proposed theory is used to determine whether parallel flow can be ignored in an actual EMLN case.

*Nomenclature*. To facilitate the description, let the $ij$th element of each incidence matrix be −1 if the positive direction of branch $j$ points to node $i$ or 1 if the branch points in the opposite direction. Unless specifically declared, the four main subscripts in the remainder of this paper are as follows.

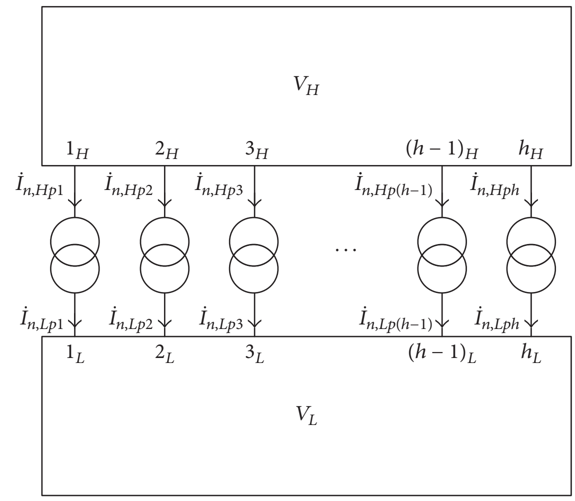

Figure 1: Analytical model of an EMLN.

| *Subscript* | *Implication* | *Example* |
|---|---|---|
| $n$ | Nodal variable | $V_n$, the nodal voltage vector |
| $b$ | Branch variable | $V_b$, the branch voltage vector |
| $H$ | The high voltage side network | $A_H$, the incidence matrix of the high voltage side network |
| $L$ | The low voltage side network | $A_L$, the incidence matrix of the low voltage side network |

In addition, we use subscripts $x$ and $p$ to divide a vector (or a matrix) into subvectors and submatrices. A subvector with subscript $x$ (subscript $p$) consists of elements that lie in the rows of the inner nodes (boundary nodes) of the vector (see the beginning of Section 2). A submatrix with double subscripts is formed in an analogous manner. Take $Y_{n,Lxp}$, which represents the submatrix of the bus admittance matrix of the low voltage side network $Y_{n,L}$, as an example. The elements of $Y_{n,Lxp}$ lie in the rows of the inner nodes and columns of the boundary nodes in $Y_{n,L}$.

## 2. Model for EMLN Parallel Flow

The basic characteristics of an EMLN are (1) a network on the high voltage side and a network on the low voltage side and (2) transformers as we model the transformer as a series connection with the internal impedance, which is converted into the low voltage side, and the ideal transformation ratio. A model of an EMLN is illustrated in Figure 1, where the blocks labeled “$V_H$” and “$V_L$” represent connected power networks with two voltage classes and arbitrary topologies. We assume that there are $h$ ideal transformers in the EMLN. The nodes on the high voltage (low voltage) side of the $h$ ideal transformer branches are hereinafter referred to as the boundary nodes of the high voltage (low voltage) side network. In addition, we designate the nodes that are not boundary nodes as inner nodes.

Denote the terminal current of the $i$th boundary node of the high voltage (low voltage) side network by $\dot{I}_{n,Hpi}$ ($\dot{I}_{n,Lpi}$), as shown in Figure 1, and denote the vectors of the terminal currents by $I_{n,Hp}$ and $I_{n,Lp}$. Then, the network equations of the high and low voltage side networks are, respectively,

$$\begin{pmatrix} Y_{n,Hxx} & Y_{n,Hxp} \\ Y_{n,Hpx} & Y_{n,Hpp} \end{pmatrix} \begin{pmatrix} V_{n,Hx} \\ V_{n,Hp} \end{pmatrix} = \begin{pmatrix} J_{n,Hx} \\ J_{n,Hp} \end{pmatrix} + \begin{pmatrix} 0 \\ -I_{n,Hp} \end{pmatrix},$$
$$\begin{pmatrix} Y_{n,Lxx} & Y_{n,Lxp} \\ Y_{n,Lpx} & Y_{n,Lpp} \end{pmatrix} \begin{pmatrix} V_{n,Lx} \\ V_{n,Lp} \end{pmatrix} = \begin{pmatrix} J_{n,Lx} \\ J_{n,Lp} \end{pmatrix} + \begin{pmatrix} 0 \\ I_{n,Lp} \end{pmatrix}, \quad (1)$$

where $Y_n$, $V_n$, and $J_n$ are the bus admittance matrix, the nodal voltage vector, and the nodal injection current vector. From Kirchhoff's current law, we have

$$J_{n,Hx} = A_{Hx} I_{b,H},$$
$$J_{n,Hp} - I_{n,Hp} = A_{Hp} I_{b,H}, \quad (2)$$

where $I_b$ represents the branch current vector and $A$ represents the incidence matrix. Denote the transposition of $A_L$ by $A_L^T = \begin{pmatrix} A_{Lx}^T & A_{Lp}^T \end{pmatrix}$. For the low voltage side network, since $V_{b,L} = A_L^T V_{n,L}$, the branch current vector gives

$$I_{b,L} = Y_{b,L} A_{Lx}^T V_{n,Lx} + Y_{b,L} A_{Lp}^T V_{n,Lp}. \quad (3)$$

Denote the diagonal matrix of the transformation ratios in Figure 1 by $K$. Let $A_{KH} = (a_{ij})_{h \times h_H}$ be the incidence matrix of the transformer branches with respect to the boundary nodes of the high voltage side network. Let $a_{ij} = 1$ if the $i$th transformer branch is associated with the $j$th boundary node and $a_{ij} = 0$ otherwise. Thus,

$$V_{n,Lp} = K^{-1} A_{KH} V_{n,Hp}. \quad (4)$$

Combining (1)–(4) gives

$$I_{b,L} = I_{\text{in},L} + C I_{b,H}, \quad (5)$$

where $I_{\text{in},L} = Y_{b,L} A_{Lx}^T Y_{n,Lxx}^{-1} J_{n,Lx}$ only depends on the nodal injection currents on the low voltage side of the EMLN, and the latter term passes through, rather than flows into, the low voltage side of the network. Therefore, we denote the latter term by $I_{T,L}$ and designate it as the transporting current,

$$I_{T,L} = C I_{b,H}, \quad (6)$$

where

$$C = \left( Y_{b,L} A_{Lp}^T - Y_{b,L} A_{Lx}^T Y_{n,Lxx}^{-1} Y_{n,Lxp} \right) \cdot K^{-1} A_{KH} \left( Y_{n,Hpp} - Y_{n,Hpx} Y_{n,Hxx}^{-1} Y_{n,Hxp} \right)^{-1} \cdot \left( A_{Hp} - Y_{n,Hpx} Y_{n,Hxx}^{-1} A_{Hx} \right). \quad (7)$$

Equation (6) is designated as the parallel current function of the EMLN, and its coefficient matrix $C$ is defined as the current transfer matrix.

Equation (6) gives the practical meaning of the transporting current. For an arbitrary possible number $k$, the $k$th transporting current is a current component of the $k$th branch current on the low voltage side network. This current component can be decomposed into a summation of several elements, each of which corresponds to a branch on the high voltage side network. Therefore, the $j$th element can be denoted by $C_{kj}$ according to (7). Accordingly, the $k$th transporting current $\dot{I}_{T,Lk}$ equals $C_{kj} \dot{I}_{b,Hj}$. It means that the $j$th branch current on the high voltage side network ($\dot{I}_{b,Hj}$) generates a current component on the $k$th branch current on the low voltage side network ($C_{kj} \dot{I}_{b,Hj}$). The mechanism of this phenomenon is entirely because of the framework ($C_{kj}$) of the power network, being independent of the power flow. It corresponds to the phenomenon of power flow transfer. If the $j$th branch fails, $\dot{I}_{b,Hj}$ becomes 0, and the $k$th branch current on the low voltage side network increases by $-C_{kj} \dot{I}_{b,Hj}$.

Since the number of transformers in an EMLN is always small, the calculation of the inverse matrix of $\widetilde{Y}_{n,Hpp}$ in (7) is straightforward. Thus, the difficulty of calculating matrix $C$ is the calculation of $Y_{n,Lxx}^{-1}$ and $Y_{n,Hxx}^{-1}$. Therefore, we propose the following network simplification method, called the main loop insulation method.

We designate the set of all paths with end points belonging to the boundary nodes of the EMLN as the main loop. Then, the main loop insulation method is used to remove all nodes and branches that are not in the main loop of the EMLN without performing additional processing.

A general method to judge whether a studied node is in the main loop is that there does not exist a removement of a single node that would isolate the studied node from the studied EMLN. The concrete method is that (1) if the nodal connectivity of the power network is larger than 1, all the nodes are in the main loop; else (2) remove all the nodes that are in the minimal nodal cut sets; (3) remove all the nodes that are isolated from the studied EMLN resulting from (2), then the remaining nodes are in the main loop. Since searching the minimal nodal cut set of a network is offline computed and is not difficult, the proposed method is effective and practical.

The main loop insulation method is based on two principles: (1) matrix $C$ in (7) is independent of the nodal injection currents; and (2) the branches that are not in the main loop generate and receive no transporting current. The first principle is apparent. The second principle can be validated by large amounts of experiments but is hard to be proved theoretically. We can explain this principle qualitatively as follows. If a branch, named branch $x$, is not in the main loop, there must exist a removement of a single node, named node $y$, that would isolate branch $x$ from the studied EMLN. Therefore, the current on branch $x$ influences, or is influenced by, the studied EMLN via node $y$. That means branch $x$ can be treated as an equivalent single node $y'$ from the perspective of the studied EMLN. According to (6), as the transporting current flows through the EMLN, it never flows into any node in the EMLN, including node $y'$. Therefore, the transporting current would not flow into branch $x$. Moreover, branch $x$ generates and receives no transporting current.

## 3. Sufficient Condition for the Parallel Flow Problem

Equation (6) shows that the transporting current equals the weighted sum of the branch currents on the high voltage side of the EMLN. Therefore, the $ij$th element of $C$ corresponds to the sensitivity of the $i$th branch flow on the low voltage side of the EMLN with respect to the $j$th branch flow on the high voltage side of the EMLN. Since high sensitivity is detrimental to system safety, it is preferable for the elements of $C$ to be small.

Denote the maximal element of $C$ by $c_m$ and denote the corresponding branch of $c_m$ on the high voltage side network by $i$-$j$. Then according to (6), the studied EMLN is the most sensitive to the removement of branch $i$-$j$. Therefore, if the studied EMLN keeps operating safely after branch $i$-$j$ is removed, we can say the studied EMLN does not have the parallel flow problem.

From the perspective of branch $i$-$j$, the high and low voltage sides of the studied EMLN are equivalent to a set of parallel transmission lines. After branch $i$-$j$ is removed, the most directly perceived parameter to reflect the proportions of the current on branch $i$-$j$ that the equivalent parallel transmission lines share is the equivalent admittance. The larger the equivalent admittance of an equivalent parallel transmission line is, the larger its branch current increases.

According to the analysis above, the equivalent model for the parallel flow problem of an EMLN can be obtained. First, remove all the branches on the low voltage side network and denote the equivalent admittances between nodes $i$ and $j$ before and after removing branch $i$-$j$, respectively, by $y_H$ and $y_{H,E}$. Then, the high voltage side network is equivalent to a set of parallel identical $n_H$-transmission lines, where

$$n_H = \frac{y_H}{(y_H - y_{H,E})}. \quad (8)$$

Second, intentionally remove all the branches that are in all the branch cut sets between nodes $i$ and $j$ on the high voltage side network of the original EMLN. Denote the consequent equivalent admittance and connectivity between nodes $i$ and $j$ by $y_L$ and $n_L$, respectively. Then, the low voltage side network is equivalent to a set of parallel identical $n_L$-transmission lines, where the equivalent admittance of each parallel transmission line is $y_{L1} = y_L/n_L$.

According to this analysis, the equivalent model of an EMLN is illustrated in Figure 2, where the branches on the high voltage side network, except branch $i$-$j$, are collectively referred to as the reserved transmission corridor, and the set of parallel identical $n_L$-transmission lines on the low voltage side network is referred to as the low voltage transmission corridor.

Let the original current on branch $i$-$j$ in Figure 2 be one unit. Then, the total current on the low voltage transmission corridor is

$$\dot{I}_{T,L} = \frac{n_L y_{L1}}{(y_H - y_{H,E})}. \quad (9)$$

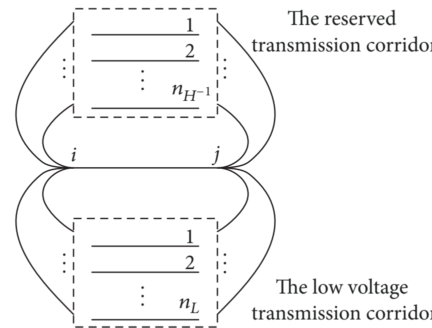


Figure 2: Equivalent model for the parallel flow problem of an EMLN.

After branch $i$-$j$ is removed, the one unit of current transfers to the two transmission corridors; the increment of the total current on the low voltage transmission corridor is

$$\Delta\dot{I}_L = \frac{1/y_{H,E}}{1/n_L y_{L1} + 1/y_{H,E}} = \frac{n_L y_{L1}}{y_{H,E} + n_L y_{L1}}. \quad (10)$$

The sufficient condition for the low voltage transmission corridor being safe after branch $i$-$j$ being removed is that the weakest branch in the low voltage transmission corridor is safe. Denote the minimal operating margin of the branches on the low voltage transmission corridor by $\delta_{\min}$ and the corresponding critical branch current by $I_{b,\max}$. To maintain the branch currents on the low voltage transmission corridor within the critical value, we have

$$\left|\Delta\dot{I}_L\right| \le \delta_{\min} I_{b,\max}. \quad (11)$$

Define the corridor occupancy ratio of branch $i$, denoted by $\alpha_i$, as the ratio of the transporting current to the $i$th branch current; then, $\alpha_i = \dot{I}_{Ti}/\dot{I}_{bi}$. Let $\alpha_L$ be the maximum corridor occupancy ratio in the low voltage transmission corridor. Accordingly, conservatively assume that the operating margin and corridor occupancy ratio of the low voltage transmission corridor are $\delta_{\min}$ and $\alpha_L$. Thus, (9) can be derived as

$$I_{b,\max} = \left|\frac{n_L y_{L1}}{\alpha_L (y_H - y_{H,E})(1 - \delta_{\min})}\right|. \quad (12)$$

By substituting (10) and (12) into (11), we obtain

$$|\alpha_L| \left|(y_H - y_{H,E})\right| \le \frac{\delta_{\min}}{1 - \delta_{\min}} \cdot \left|(y_{H,E} + n_L y_{L1})\right|. \quad (13)$$

Since

$$\begin{aligned} |y_H| - |y_{H,E}| &\le \left|(y_H - y_{H,E})\right|, \\ \left|(y_{H,E} + n_L y_{L1})\right| &\le (|y_{H,E}| + n_L |y_{L1}|), \end{aligned} \quad (14)$$

we have

$$|\alpha_L| |y_H| - |\alpha_L| |y_{H,E}| \le \frac{\delta_{\min}}{1 - \delta_{\min}} \cdot (|y_{H,E}| + n_L |y_{L1}|), \quad (15)$$

that is,

$$n_L \geq \frac{1-\delta_{\min}}{\delta_{\min}} |\alpha_L| \frac{|y_H|}{|y_{L1}|} - \left(\frac{|\alpha_L|}{\delta_{\min}} + 1 - |\alpha_L|\right) \frac{|y_{H,E}|}{|y_{L1}|}. \quad (16)$$

Since $1/n_H = (y_H - y_{H,E})/y_H = 1 - y_{H,E}/y_H$ gives $y_H/y_{H,E} = 1/(1-1/n_H) = n_H/(n_H-1)$, we obtain

$$|y_H| = \left|\frac{n_H}{n_H - 1}\right| |y_{H,E}|. \quad (17)$$

Substituting (17) into (16) gives

$$n_L \geq \left(|\alpha_L|\left(\frac{1}{\delta_{\min}} - 1\right)\left(\left|\frac{n_H}{n_H-1}\right| - 1\right) - 1\right) \frac{|y_{H,E}|}{|y_{L1}|}. \quad (18)$$

Conservatively, let the sensitivity of each branch current on the low voltage transmission corridor with respect to each branch current on the reserved transmission corridor be $c_m$. Thus,

$$\frac{1}{c_m} = \frac{y_{H,E}}{y_{L1}} \cdot \frac{1}{n_H - 1}. \quad (19)$$

Substituting (19) into (18) gives

$$n_L \geq \left(|\alpha_L|\left(\frac{1}{\delta_{\min}} - 1\right)\left(|n_H| - |n_H - 1|\right) - |n_H - 1|\right) \cdot \frac{1}{|c_m|}. \quad (20)$$

Therefore, an EMLN that satisfies (20) does not have a parallel flow problem.

Note that $n_H$ in (20) should be derived from (8). The practical meaning of $n_H$ is the connection quality of the high voltage side network from the perspective of the low voltage side network. For example, (1) if the high voltage side network is actually a set of parallel identical multi-transmission lines, then $n_H$ is the number of parallel lines; (2) if the high voltage side network is a set of parallel nonidentical paths, and the admittance of the studied path is $y_{H1}$, then from the perspective of the low voltage side network, cutting off the studied path is equivalent to cutting off one of the parallel identical multi-transmission lines, the total admittance of which is $n_H \times y_{H1}$. $|n_H|$ is usually a complex number. For example, a set of dual-transmission lines probably means $|n_H| \approx 2$ rather than $n_H = 2$.

The practical meaning of (20) can be expanded into, but is not limited to, the following 3 aspects:

(1) If the high voltage side of the EMLN is a set of dual-transmission lines, then $|n_H| \approx 2$. Under this condition, if the operating margins of the branches on the low voltage side network are greater than 50%, then the sufficient condition for EMLN safety is $n_L \geq 0$; that is, there is no requirement on the configuration parameter of the low voltage side network. As long as the dual-transmission lines on the high voltage side network satisfy the $N-1$ criterion, the EMLN is able to operate safely.

(2) If the high voltage side of the EMLN is, or is considered as, a single-transmission line, then $|n_H| = 1$. Under this condition, if the operating margins of the branches on the low voltage side network are greater than 50%, then the sufficient condition for EMLN safety is

$$n_L \geq \frac{|\alpha_L|}{|c_m|}. \quad (21)$$

Note that $|c_m|$ is sometimes so small that (21) is difficult to satisfy. The power flow on the high voltage side of the EMLN should be restricted.

(3) If the high voltage side of the EMLN is, or is considered as, a single-ring, then according to (8), $|n_H|$ usually belongs to $(1, 2]$. For example, if $|n_H| = 1.5$, then with the operating margins of the branches on the low voltage side network greater than 50%, the sufficient condition for EMLN safety is $n_L \geq (|\alpha_L| - 0.5)/|c_m|$. Moreover, the values of $|n_H|$, $|\alpha_L|$, $|c_m|$, and $\delta_{\min}$ in (20) depend on practical conditions; therefore, the specific circumstances alter the actual results.

Assume that given $n_L \geq 1$, (20) always holds. Therefore,

$$\left(|\alpha_L|\left(\frac{1}{\delta_{\min}} - 1\right)\left(|n_H| - |n_H - 1|\right) - |n_H - 1|\right) \frac{1}{|c_m|} \leq 1. \quad (22)$$

The sufficient condition of (22) is

$$|n_H| \geq \frac{1}{\delta_{\min}} - |c_m|. \quad (23)$$

Therefore, if $|n_H|$ satisfies (23), (22) always holds. Specially, an EMLN that satisfies (23) is designated as a strong EMLN; otherwise, it is designated as a weak EMLN.

According to the analysis above, a strong EMLN is sure to operate safely, whereas a weak EMLN has some requirements on the low voltage side network. Assume that the operating margins of the branches on the low voltage side network are more than 50%; then, according to (20), the requirements on $n_L$ for some typical EMLNs are listed in Table 1, where the first column is the type of EMLN and the other columns are the minimum values of $n_L$.

Accordingly, the last column of Table 1 shows that if $n_H = 1.9$, all the studied types of EMLNs are strong EMLNs. Moreover, the minimum values of $n_H$ required for these types of EMLNs to be strong EMLNs are illustrated in Table 2.

Generally, an EMLN that satisfies (20) does not have a parallel flow problem; otherwise, it needs to operate in a restricted way or to adopt open loop planning.

## 4. Case Study

This section analyzes a practical EMLN case to determine whether the EMLN has a parallel flow problem. The case is from the IEEE 30-bus test system, which is illustrated in Figure 3. The detailed data of the studied system refers to [29].

According to Figure 3, nodes $\{11, 13, 26, 29, 30\}$ are not in the main loop. The boundary nodes of the high voltage side network are $\{6, 4, 28\}$. The boundary nodes on the low voltage side network are the new nodes $\{31, 32, 33, 34\}$, which are created by the model of the transformers in Figure 1. The

Table 1: Minimum values of $n_L$ of some typical EMLNs.

| Type of EMLN | Minimum values of $n_L$ | | | |
|---|---|---|---|---|
| | $n_H = 1$ | $n_H = 1.33$ ① | $n_H = 1.5$ ② | $n_H = 1.9$ ③ |
| 1000 kV/500 kV | 4.0178 | 2.6785 | 2.0089 | 0.4018 |
| 765 kV/345 kV | 5.0896 | 3.3931 | 2.5448 | 0.5090 |
| 500 kV/220 kV | 4.9297 | 3.2864 | 2.4648 | 0.4930 |
| 380 kV/220 kV | 2.8443 | 1.8962 | 1.4222 | 0.2844 |
| 230 kV/115 kV | 4.4419 | 2.9613 | 2.2210 | 0.4442 |

① For example, the high voltage side of the EMLN consists of a single line and a parallel path with impedance distance approximately 3 times that of the single line. ② For example, the high voltage side of the EMLN consists of a single line and a parallel path with impedance distance approximately 2 times that of the single line. ③ The high voltage side of the EMLN consists of approximately dual-transmission lines.

Table 2: Minimum values of $n_H$ for the studied types of EMLNs to be strong EMLNs.

| Type of EMLN | Minimum values of $n_H$ |
|---|---|
| 1000 kV/500 kV | 1.7511 |
| 765 kV/345 kV | 1.8035 |
| 500 kV/220 kV | 1.7971 |
| 380 kV/220 kV | 1.6484 |
| 230 kV/115 kV | 1.7749 |

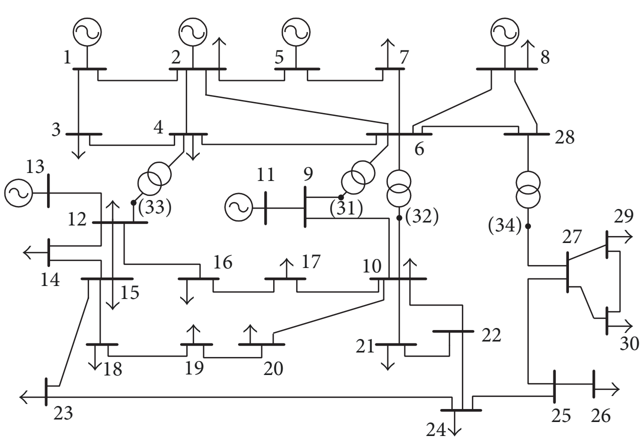


Figure 3: The IEEE 30-bus test system.

ratio matrix of this case is $K = \text{diag}(k_{6\text{-}9}, k_{6\text{-}10}, k_{4\text{-}12}, k_{28\text{-}27})$. And,

$$A_{KH} = \begin{pmatrix} 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}^T. \quad (24)$$

Then, calculate the current transfer matrix $C$. According to (6), the operating data of the studied system is listed in Tables 3 and 4.

From Table 4, the transporting currents on branches {9-11, 12-13, 25-26, 27-29, 27-30, 29-30} are zero, which echoes the second principle in Section 2. All the transporting currents in Table 4 are not large with respect to the branch currents in Table 3. Therefore the parallel flow problem of the studied system is slight. In comparison, the transporting currents on branches {9-10, 9-31, 12-33} are relatively larger than other transporting currents. These branches are transformer branches according to Figure 3. Therefore, the parallel flow problem of the transformer branches in the studied system is more serious.

Table 3: Branch currents on the high voltage side network (p.u.)

| Branch Label | Branch Current |
|---|---|
| 1-2 | 1.6478 |
| 1-3 | 0.82921 |
| 2-5 | 0.78963 |
| 2-6 | 0.57872 |
| 2-4 | 0.42271 |
| 3-4 | 0.80508 |
| 5-7 | 0.19186 |
| 7-6 | 0.37779 |
| 8-6 | 0.30002 |
| 8-28 | 0.017095 |
| 6-4 | 0.72867 |
| 6-28 | 0.18493 |

Next, we utilize the equivalent model in Section 3 to assess the parallel flow problem further. Note that the maximum modulus in $C$ is $c_m = 0.0596 - 0.0073i$. The corresponding branches on the high and low voltage sides of the EMLN are 4-6 and 4-12, respectively. According to (8), the value of $n_H$ between nodes 4 and 6 is 1.1776, which is smaller than 2. It is because although the connectivity between nodes 4 and 6 on the high voltage side network is up to 3, the impedances of branches 2-4 and 2-6 are much larger than the impedance of branch 4-6 (more than 5 times each), which makes the parallel path 4-2-6 fail to substantially reduce the equivalent impedance between nodes 4 and 6. Because the impedances of the other paths are much larger than that of path 4-2-6, it is reasonable that there are only 1.18 equivalent parallel identical branches between nodes 4 and 6.

Assume that the operating margins of the branches on the low voltage side network are greater than 50%. According to (20), the sufficient condition for the studied EMLN to not have the parallel flow problem is at least 3.2264 parallel paths between nodes 12 and 10 on the low voltage side network. In addition, the equivalent impedance of each parallel path is similar to that of path 4-12-16-17-10-6. Since there are

Table 4: Transporting currents on the low voltage side network (p.u.).

| Branch Label | Transporting Current |
|---|---|
| 9-10 | 0.024724 |
| 9-11 | 0 |
| 9-31 | 0.024724 |
| 10-17 | 0.012479 |
| 10-20 | 0.0070253 |
| 10-21 | 0.0041807 |
| 10-22 | 0.0027323 |
| 10-32 | 0.013252 |
| 12-13 | 0 |
| 12-14 | 0.0025869 |
| 12-15 | 0.010099 |
| 12-16 | 0.012479 |
| 12-33 | 0.025079 |
| 14-15 | 0.0025869 |
| 15-18 | 0.0070253 |
| 15-23 | 0.0056423 |
| 16-17 | 0.012479 |
| 18-19 | 0.0070253 |
| 19-20 | 0.0070253 |
| 21-22 | 0.0041807 |
| 22-24 | 0.0069128 |
| 23-24 | 0.0056423 |
| 24-25 | 0.0013838 |
| 25-26 | 0 |
| 25-27 | 0.0013838 |
| 27-29 | 0 |
| 27-30 | 0 |
| 27-34 | 0.0013838 |
| 29-30 | 0 |
| 15-23 | 0.0056423 |

actually 3 paths (slightly less than 3.2264) on the low voltage transmission corridor, the studied EMLN has a minor parallel flow problem.

A simple way to eliminate the parallel flow problem is to add an additional transformer branch between nodes 4 and 12 to reduce the impedance of path 4-12-16-17-10-6. In that case, according to (20), the sufficient condition for the studied EMLN to not have a parallel flow problem is at least 2.6033 parallel paths between nodes 12 and 10 on the low voltage side network. Since $3 > 2.6033$, the sufficient condition (20) holds; therefore, the improved EMLN does not have a parallel flow problem.

Another way to eliminate the parallel flow problem is to upgrade the EMLN to a strong EMLN. According to (23), the sufficient condition for the studied EMLN to be a strong EMLN is at least 1.94 parallel identical transmission lines between nodes 4 and 6 on the high voltage side network. Therefore, adding a transmission line between nodes 4 and 6 is feasible.

In general, the studied EMLN has a slight parallel flow problem, which can be easily eliminated by investing in new facilities.

## 5. Conclusions

Parallel flow, which threatens the safety of power networks, is a primary characteristic of EMLNs. To objectively determine whether an EMLN has a parallel flow problem, this paper formulates the parallel flow of an EMLN and derives the sufficient condition for an EMLN to not have a parallel flow problem.

First, this paper models general EMLNs. According to the network equations of both the high and low voltage sides of the EMLN, this paper derives the system of linear functions of the transporting currents on the low voltage side network with respect to the branch currents on the high voltage side network. This system of linear functions is called the parallel current function of the EMLN and can be utilized to assess the extent of influence of the parallel flow. The coefficient matrix of the parallel current function is designated as the current transfer matrix, which can be calculated conveniently using the main loop insulation method.

Second, according to the current transfer matrix, this paper makes the high and low voltage side networks equivalent to two sets of parallel identical multi-transmission lines. By taking the operating margins of the low voltage side network into account, this paper derives the sufficient condition for safe EMLN operation. The sufficient condition can be utilized to determine whether an EMLN has a parallel flow problem and to reveal simple approaches to diminishing parallel flow.

According to the sufficient condition, parallel flow can be ignored in EMLNs that do not have a parallel flow problem, whereas EMLNs that may have a parallel flow problem require additional safety checks.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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