Appendix A

A.1 Morphological Preliminaries

Erosion and dilation are the basic operations of mathematical morphology (MM). Other complex operators such as opening and closing MM operators are synthesized using these basic operators. They are defined on the basis of topology theory. Let, $f(m)$ and $g(n)$ be the input signal and SE respectively defined in domains, $C_f = c_0, c_1, c_2...c_m$ and $D_g = d_0, d_1, d_2...d_n$ respectively with $m > n$, where m and n are the integers. The dilation δ_g and erosion ϵ_g operation are explained as follows [99] -

$$\delta_g(f)(m) = (f \oplus g)(m) = \max_{n \in g}(f(m-n))$$

$$\varepsilon_g(x)(m) = (f \ominus g)(m) = \min_{n \in g}(f(m+n))$$

where $\oplus$ and $\ominus$ are the dilation and erosion operators. Using the dilation and erosion operators, the closing and opening operators are defined. The opening of $f(m)$ by $g(n)$ is denoted by $f \circ g$, is defined as dilation of eroded signal $f \ominus g$ by g -

$$\phi_g = (f \circ g)(m) = ((f \ominus g) \oplus g)(m)$$

Similarly, closing of $f(m)$ by $g(n)$, denoted by $f \bullet g$ is expressed as -

$$\gamma_g = (f \bullet g)(m) = ((f \oplus g) \ominus g)(m)$$

Erosion and dilation operators forms a pair of adjunction which has the following proposition [99]-

$$\varepsilon\delta\varepsilon = \phi\varepsilon = \varepsilon\gamma = \varepsilon$$

$$\delta\varepsilon\delta = \gamma\delta = \delta\phi = \delta$$

Since, $\varepsilon\delta$ makes ϕ, whilst $\delta\varepsilon$ forms γ. This proposition helps to simplify the analysis and details analysis operators of MUDW decomposition scheme.

A.2 Coupled Wavelet Description

The signal analysis ($\psi_i^{\uparrow}$), synthesis ($\psi_i^{\downarrow}$) and detail analysis operator ($\omega_i^{\uparrow}$) of the coupled wavelet must satisfy the pyramid condition in order to guarantee no information lost and non redundant decomposition. The pyramid conditions can be explained as follows [100] -

$$\psi_i^{\uparrow}(\psi_i^{\downarrow}(x,y)) = x,\ if\ x \in U_{i+1}, y \in W_{i+1}$$

$$\omega_i^{\uparrow}(\psi_i^{\downarrow}(x,y)) = y,\ if\ x \in U_{i+1}, y \in W_{i+1}$$

For complete signal representation, the $(\psi_i^{\uparrow}\omega_i^{\uparrow}) : U_i \to U_{i+1} \times W_{i+1}$ and $\psi_i^{\downarrow} : U_{i+1} \times W_{i+1} \to U_i$ need to be inverse to each other, which leads to another condition -

$$\psi_i^{\downarrow}(\psi_i^{\uparrow}(x), \omega_i^{\uparrow}(x)) = x,\ if\ x \in U_i$$

Furthermore, for input signal $x_i \in U_i$ and $y_i \in W_i$, the recursive analysis scheme will be [99] -

$$x_{i+1} = \psi_i^{\uparrow}(x_i) \in U_{i+1}$$

$$y_{i+1} = \omega_i^{\uparrow}(x_i) \in W_{i+1}, i \geq 0$$

By recursive synthesis scheme -

$$x_i = \psi_i^{\downarrow}(x_{i+1}, y_{i+1})$$

It shows that the decomposition scheme is invertible. The above mentioned signal representation scheme is referred to as coupled wavelet decomposition scheme [100].

Appendix B

B.1 Graph Theory Preliminaries

Lemma I: If a point f lies on the shortest path between two arbitrary nodes n_1 and n_2 on the graph g, then this path can be represented as the union of the shortest path between node n_1 and f, and the one between f and n_2.

Proof: The proof is rather straightforward. If either of these two paths isn't the shortest one, replacing it with the corresponding shortest path would result in a shorter path between the nodes. This, in turn, would lead to a contradiction.

Lemma II: Assuming a branch between nodes n_1 and n_2, i.e..; $(n_1, n_2) \in b$. For any shortest path between nodes n_2 and n_3 passes through node n_1, then for any random point f on the branch (n_1, n_2), the node n_1 must lie on the shortest path between f and n_3.

Proof: Based on *Lemma I* and since $P^{min}_{n_2,f}$ passes through node n_1, which concludes that -

$$P^{min}_{n_2,f} = \{(n_2, n_1)\} \cup P^{min}_{n_1,f} \Rightarrow D_{n_2,f} = D_{n_2,n_1} + D_{n_1,f} \tag{B.1}$$

The following identity is valid for the point f located on the branch (n_1, n_2) as shown in Fig. B.1.

$$D_{n_2,n_1} = D_{n_2,f} + D_{f,n_1} \tag{B.2}$$

Since travel in only two directions is possible, any path from the point f to any other node in the graph will inevitably pass through either the node n_1 or n_2 . Consequently, even the shortest path from f to any node n_3 follows this pattern. Therefore, it can be deduced from Lemma I that -

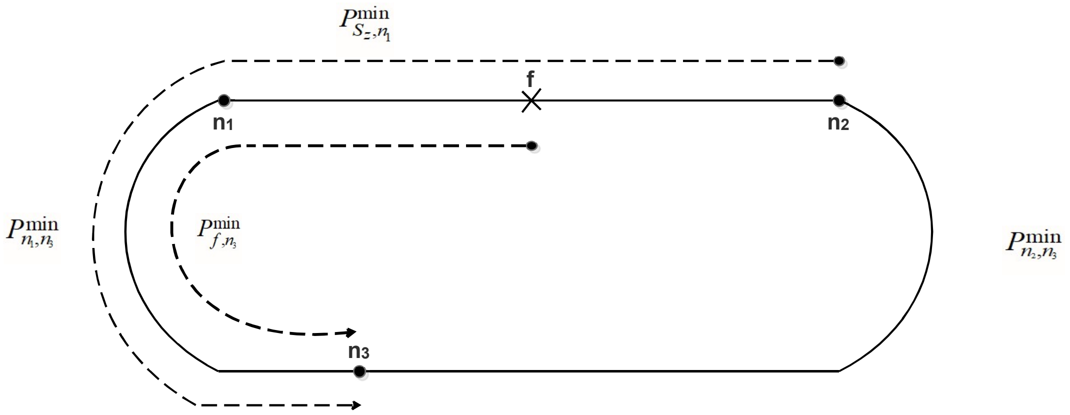

Figure B.1: Graph diagram representation for *Lemma II*

$$P^{min}_{f,n_3} = min(P^{min}_{f,n_1} \cup P^{min}_{n_1,n_3}, P^{min}_{f,n_2} \cup P^{min}_{n_2,n_3}) \tag{B.3}$$

As per (B.1) and (B.2), it can be easily concluded that $D_{f,n_1} = D_{n_1,n_3} < D_{f,n_2} + D_{n_2,n_3}$. Therefore, concerning (B.3), the shortest route from the point f to node n_3, denoted as P^{min}_{f,n_3}, is the path that goes through node n_1. Consequently, this establishes the validity of the *Lemma II*.

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List of Publications

1. **Mahitosh Banafer**, and Soumya R. Mohanty, "A travelling wave based primary and backup protection for MMC-MTDC transmission system using morphological un-decimated wavelet scheme." *Electric Power Systems Research*,vol. 212, p. 108367, 2022, doi:https://doi.org/10.1016/j.epsr.2022.108367 (Published).
2. **Mahitosh Banafer**, and Soumya R. Mohanty, "Traveling Wave based Primary Protection and Fault Localization Scheme for MTDC Grid Considering IEC 61869-9 Measurement Standard." *IEEE Transactions on Instrumentation and Measurement*, vol. 72, pp. 1-16, 2023, doi: https://doi.org/10.1109/TIM.2023.3271735.2023 (Published).
3. **Mahitosh Banafer** and Soumya R. Mohanty, "Single ended traveling wave based fault localization scheme for MTDC grid using sliding matrix pencil technique", *IEEE System Journal* (Submitted).
4. **Mahitosh Banafer**, S. R. Mohanty and T. Prakash, "A Traveling Wave based Wide Area Backup Protection for HVAC Grid Considering Effects of MMC interfaced HVDC grid", *IEEE Transaction on Power Delivery* (Submitted).
5. **Mahitosh Banafer**, and Soumya R. Mohanty, "An efficient travelling wave based fault localization for MTDC transmission system." 9th *IEEE International Conference on Power Systems (ICPS)*,pp. 1-6, IEEE, 2021, doi: https://doi.org/10.1109/ICPS52420.2021.9670418. (Published).