A Game-Theoretic Approach for Enabling Transactive Energy Frameworks among Networked Microgrids

KKT Formulation and Solving Technique for EPEC problem

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Nomenclature

Indexes

b	Index of energy storage units in set B.
g	Index of distributed generators in set G.
h	Index of transmission grid interface in set H.
i, j	Indices of nodes in set I.
l	Index of demands in set L.
m, k	Index of microgrids in set M.
r	Index of energy renewable resource units in set R.
t	Index of times in set T.

Sets

Λ_m^B	Set of energy storage units in microgrid m.
Λ_m^L	Set of demands in microgrid m.
Λ_m^R	Set of renewable resource units in microgrid m.
Θ_i^L	Set of demands connected to node i.

Θ_i^M Set of microgrids connected to node i.

Θ_i^T Set of transmission grid interface connected to node i.

Θ_m^G Set of distributed generators in microgrid m.

$B(i)$ Set of nodes directly connected to node i.

REF Reference bus in distribution network.

Parameters

ηb_m Efficiency of energy storage system in microgrid m (%).

$b_{i,j}$ Susceptance of line connecting node i and j.

C_m^E Cost of loss-of-load in microgrid m ($/kWh).

C_t^{TS} Price of buying electricity by the distribution system operator from transmission grid at time t ($/kWh).

Cb_m Cost of charging/discharging storage resources in microgrid m ($/kWh).

Cg_m Cost of power production of distributed generator in microgrid m ($/kWh).

$D_{m,t}$ Power demand in microgrid m at time t (kW).

EB_m Energy capacity of installed energy storage system in microgrid m (kWh).

$Gr_{m,t}$ Power generated by renewable resources in microgrid m at time t (kW).

$L_{i,t}$ Power demand of electric loads at node i at time t in distribution system (kW).

$P^{max,TM}$ Maximum power exchange in transactive market (kW).

$P^{max,TS}$ Maximum power purchased from transmission grid (kW).

P_m^{max} Maximum power sold/bought by microgrid m (kW).

$P_{i,j}^{f,max}$ Maximum power flow through branch ij (kW).

Pd_m Power rating of energy storage system of microgrid m (kW).

Pg_m^{max} Maximum power output of the distributed generator in microgrid m (kW).

SoC_m^{max} Maximal state of charge of energy storage system in microgrid m.

SoC_m^{min} Minimal state of charge of energy storage system in microgrid m.

Variables

$\mu_{m,t}^{b,D}$ Binary variable of microgrid m at time t to indicate its power purchasing status in the DSO based market, 1 means the microgrid is purchasing power in DM, 0 means otherwise.

$\mu_{m,t}^{b,T}$ Binary variable of microgrid m at time t to indicate its power purchasing status in the transactive market, 1 means the microgrid is purchasing power in TM, 0 means otherwise.

$\mu_{m,t}^{s,T}$ Binary variable of microgrid m at time t to indicate its power selling status in the transactive market, 1 means the microgrid is selling power in TM, 0 means otherwise.

$\mu_{m,t}^{s,D}$ Binary variable of microgrid m at time t to indicate its power selling status in the DSO based market, 1 means the microgrid is selling power in DM, 0 means otherwise.

$\theta_{i,t}$ Voltage phase angle of bus i at time t.

$b_{m,t}$ Bidding price of microgrid m in the transactive market at time t (\$/kWh).

$o_{m,t}$ Offering price of microgrid m in the transactive market at time t (\$/kWh).

P_t^{TS} Power purchased by distribution system operator from transmission system at time t (kW).

$P_{m,t}^{b,DM}$ Power bought from distribution system operator in the DSO based market by microgrid m (kW).

$P_{m,t}^{b,TM}$ Power bought in the transactive market by microgrid m (kW).

$P_{m,t}^{s,DM}$ Power sold to the distribution system operator in the DSO based market by microgrid m (kW).

$P_{m,t}^{s,TM}$ Power sold in the transactive market by microgrid m (kW).

$P_{m,t}^{sh}$ Load shedding of microgrid m at time t (kW).

$Pd_{m,t}/Pc_{m,t}$ Discharge/charge power of energy storage system in microgrid m at time t (kW).

$Pg_{m,t}$ Power output of distributed generator in microgrid m at time t (kW).

$PL_{i,t}$ Load shedding at node i in the distribution network at time t (kW).

$Pr_{m,t}$ Power used by microgrid m at time t from renewable sources (kW).

$RC_{m,t}$ Stored energy in energy storage system in microgrid m at time t (kWh).

1 Problem description

This work is the detailed mathematical formulation of ”A Game-Theoretic Approach for Enabling Transactive Energy Frameworks among Networked Microgrids”.

2 System Formulation

2.1 Upper Level Problem – Microgrid Operator

$$\begin{aligned}
\min_{\Xi_{MO}} \quad & \sum_{t} \left[\sum_{\Lambda_m^G} Cg_m Pg_{m,t} + \sum_{\Lambda_m^B} \left(Pd_{m,t} + Pc_{m,t}\right) Cb_m + \sum_{\Lambda_m^L} C_m^E P_{m,t}^{sh} \right. \\
& \left. o_{m,t} P_{m,t}^{s,TM} - b_{m,t} P_{m,t}^{b,TM} + \sum_{\Theta_i^M} \left(\lambda_{i,t}^{DM} P_{m,t}^{b,DM} \right) - 0.3 C_t^{TS} P_{m,t}^{s,DM} \right] && (1) \\
\text{s.t.} \quad & \sum_{\Lambda_m^G} Cg_m Pg_{m,t} + \sum_{\Lambda_m^B} \left(Pd_{m,t} \eta b_m - Pc_{m,t}/\eta b_m\right) + \sum_{\Lambda_m^R} Pr_{m,t} \\
& + P_{m,t}^{b,DM} + P_{m,t}^{b,TM} - P_{m,t}^{s,DM} - P_{m,t}^{s,TM} = \sum_{\Lambda_m^L} \left(D_{m,t} - P_{m,t}^{sh} \right) \ (\lambda_{m,t}^{MG}) \quad \forall t && (2) \\
& o_{m,t} \geq 0 \quad (\beta_{m,t}^{o}) \quad \forall t && (3) \\
& b_{m,t} \geq 0 \quad (\beta_{m,t}^{b}) \quad \forall t && (4) \\
& 0 \leq Pg_{m,t} \leq Pg_m^{max} \quad (\beta_{m,t}^{gmin}, \beta_{m,t}^{gmax}) \quad \forall t && (5) \\
& 0 \leq Pr_{m,t} \leq Gr_{m,t} \quad (\beta_{m,t}^{prmin}, \beta_{m,t}^{prmax}) \quad \forall t && (6) \\
& SoC^{min} EB_m \leq RC_{m,t} \leq SoC^{max} EB_m \quad (\beta_{m,t}^{rmin}, \beta_{m,t}^{rmax}) \quad \forall t && (7) \\
& RC_{m,t+1} = RC_{m,t} - Pd_{m,t+1} + Pc_{m,t+1} \quad (\beta_{m,t}^{rct}) \quad \forall t && (8) \\
& RC_{m,t0} = RC_{m,t24} \quad (\beta_{m,t}^{rcmax}) \quad \forall t && (9) \\
& 0 \leq Pd_{m,t} \leq PB_m \quad (\beta_{m,t}^{pdmin}, \beta_{m,t}^{pdmax}) \quad \forall t && (10) \\
& 0 \leq Pc_{m,t} \leq PB_m \quad (\beta_{m,t}^{pcmin}, \beta_{m,t}^{pcmax}) \quad \forall t && (11) \\
& 0 \leq P_{m,t}^{sh} \leq D_{m,t} \quad (\beta_{m,t}^{pshmin}, \beta_{m,t}^{pshmax}) \quad \forall t && (12) \\
& P_{m,t}^{b,DM} + P_{m,t}^{b,TM} \leq P_m^{max} \quad (\beta_{m,t}^{bmax}) \quad \forall t && (13) \\
& P_{m,t}^{s,DM} + P_{m,t}^{s,TM} \leq P_m^{max} \quad (\beta_{m,t}^{smax}) \quad \forall t && (14) \\
& 0 \leq P_{m,t}^{b,DM} \leq P_m^{max} \mu_{m,t}^{b,D} \quad (\beta_{m,t}^{bDMmin}, \beta_{m,t}^{bDMmax}) \quad \forall t && (15) \\
& 0 \leq P_{m,t}^{s,DM} \leq P_m^{max} \mu_{m,t}^{s,D} \quad (\beta_{m,t}^{sDMmin}, \beta_{m,t}^{sDMmax}) \quad \forall t && (16) \\
& \mu_{m,t}^{s,D} + \mu_{m,t}^{b,D} \leq 1 \quad \forall t && (17) \\
& \mu_{m,t}^{s,T} + \mu_{m,t}^{b,T} \leq 1 \quad \forall t && (18) \\
& \mu_{m,t}^{s,T},\ \mu_{m,t}^{b,T},\ \mu_{m,t}^{s,D},\ \mu_{m,t}^{b,D} \in \{0,1\} \quad \forall t && (19)
\end{aligned}$$

Where $\Xi_{MO} = \{Pg_{m,t}, Pd_{m,t}, Pc_{m,t}, P^{sh}_{m,t}, Pr_{m,t}, o_{m,t}, b_{m,t}, P^{b,DM}_{m,t}, P^{s,DM}_{m,t}, \mu^{s,D}_{m,t}, \mu^{b,D}_{m,t}, \mu^{s,T}_{m,t}, \mu^{b,T}_{m,t}\}$.

2.2 Lower Level Problem – Transactive Energy Operator

$$\min_{\Xi_{TEO}} \quad \sum_t \sum_m \left(o_{m,t} P^{s,TM}_{m,t} - b_{m,t} P^{b,TM}_{m,t} \right) \tag{20}$$

$$\text{s.t.} \quad \sum_m \left(P^{s,TM}_{m,t} - P^{b,TM}_{m,t} \right) = 0 \quad (\lambda^{TM}_t) \qquad \forall t \tag{21}$$

$$0 \leq P^{s,TM}_{m,t} \leq P^{max,TM} \mu^{s,T}_{m,t} \quad (\gamma^{sTMmin}_{m,t}, \gamma^{sTMmax}_{m,t}) \qquad \forall t \tag{22}$$

$$0 \leq P^{b,TM}_{m,t} \leq P^{max,TM} \mu^{b,T}_{m,t} \quad (\gamma^{bTMmin}_{m,t}, \gamma^{bTMmax}_{m,t}) \qquad \forall t \tag{23}$$

Where $\Xi_{TEO} = \{P^{s,TM}_{m,t}, P^{b,TM}_{m,t}\}$.

2.2.1 Optimally conditions for the Transactive Energy Operator

$$\sum_{m,t} \Big(o_{m,t} P^{s,TM}_{m,t} - b_{m,t} P^{b,TM}_{m,t} + \gamma^{sTMmax}_{m,t} P^{max,TM}$$

$$+ \gamma^{bTMmax}_{m,t} P^{max,TM} \Big) = 0 \quad (\beta^{str}_{m,t}) \tag{24}$$

$$o_{m,t} - \lambda^{TM}_t - \gamma^{sTMmin}_{m,t} + \gamma^{sTMmax}_{m,t} = 0 \quad (\beta^{oTM}_{m,k,t}) \qquad \forall m,t \tag{25}$$

$$-b_{m,t} + \lambda^{TM}_t - \gamma^{bTMmin}_{m,t} + \gamma^{bTMmax}_{m,t} = 0 \quad (\beta^{bTM}_{m,k,t}) \qquad \forall m,t \tag{26}$$

$$\gamma^{sTMmin}_{m,t} \geq 0 \quad (\beta^{\gamma,smin}_{m,k,t}) \qquad \forall m,t \tag{27}$$

$$\gamma^{sTMmax}_{m,t} \geq 0 \quad (\beta^{\gamma,smax}_{m,k,t}) \qquad \forall m,t \tag{28}$$

$$\gamma^{bTMmin}_{m,t} \geq 0 \quad (\beta^{\gamma,bmin}_{m,k,t}) \qquad \forall m,t \tag{29}$$

$$\gamma^{bTMmax}_{m,t} \geq 0 \quad (\beta^{\gamma,bmax}_{m,k,t}) \qquad \forall m,t \tag{30}$$

$$0 \leq P^{s,TM}_{m,t} \leq P^{max,TM} \mu^{s,T}_{m,t} \quad (\beta^{sTMmin}_{m,k,t}, \beta^{sTMmax}_{m,k,t}) \qquad \forall m,t \tag{31}$$

$$0 \leq P^{b,TM}_{m,t} \leq P^{max,TM} \mu^{b,T}_{m,t} \quad (\beta^{bTMmin}_{m,k,t}, \beta^{bTMmax}_{m,k,t}) \qquad \forall m,t \tag{32}$$

$$\sum_m \left(P^{s,TM}_{m,t} - P^{b,TM}_{m,t} \right) = 0 \quad (\beta^{TM}_{m,k,t}) \qquad \forall t \tag{33}$$

2.3 Lower Level Problem – Distribution System Operator

$$
\begin{aligned}
\min_{\Xi_{DSO}} \quad & \sum_{t} \left(C_t^{TS} P_t^{TS} + C_m^{E} PL_{i,t} \right) && && (34) \\
\text{s.t.} \quad & \sum_{\Theta_i^T} P_t^{TS} + \sum_{\Theta_i^M} \left(P_{m,t}^{s,TM} + P_{m,t}^{s,DM} - P_{m,t}^{b,TM} - P_{m,t}^{b,DM} \right) \\
& + \sum_{j \in B(i)} \left(b_{i,j} \left(\delta_{i,t} - \delta_{j,t} \right) \right) = \sum_{\Theta_i^L} \left(L_{i,t} - PL_{i,t} \right) \left(\lambda_t^{DM} \right) && \forall i, t && (35) \\
& - P_{i,j}^{fmax} \leq b_{i,j} \left(\delta_{i,t} - \delta_{j,t} \right) \leq P_{i,j}^{fmax} \; \left(\rho_{i,j,t}^{fmin}, \rho_{i,j,t}^{fmax} \right) && \forall i, j \in B(i), \forall t && (36) \\
& 0 \leq P_t^{TS} \leq P^{max,TS} \quad \left(\rho_{i,t}^{pTSmin}, \rho_{i,t}^{bTMmax} \right) && \forall i, t && (37) \\
& 0 \leq PL_{i,t} \leq L_{i,t} \quad \left(\rho_{i,t}^{PLmin}, \rho_{i,t}^{PLmax} \right) && \forall i, t && (38) \\
& \delta_{REF,t} = 0 \quad \left(\rho_{REF,t} \right) && i = REF, \forall t && (39)
\end{aligned}
$$

Where $\Xi_{TEO} = \{P_t^{TS}, PL_{i,t}, \delta_{i,t}\}$.

2.3.1 Complementarity constrains for the Distribution Network Operator

$$
\begin{aligned}
& C_t^{TS} - \lambda_t^{DM} - \rho_{i,t}^{pTSmin} + \rho_{i,t}^{bTMmax} = 0 && \forall i, t && (40) \\
& C_m^{E} - \lambda_t^{DM} - \rho_{i,t}^{PLmin} + \rho_{i,t}^{PLmax} = 0 && \forall i, t && (41) \\
& C_m^{E} + \lambda_t^{DM} - \rho_{i,t}^{PLmin} + \rho_{i,t}^{PLmax} = 0 && \forall i, t && (42) \\
& \sum_{j \in B(i)} \left(b_{i,j} \Big(\lambda_{i,t} - \lambda_{j,t} \Big) \right) - \sum_{j \in B(i)} \left(b_{i,j} \left(\rho_{i,j,t}^{fmin} - \rho_{j,i,t}^{fmin} \right) \right) \\
& + \sum_{j \in B(i)} \left(b_{i,j} \left(\rho_{i,j,t}^{fmax} - \rho_{j,i,t}^{fmax} \right) \right) + \left(\rho_{REF,t} \right)_{i=REF} = 0 && \forall i, t && (43) \\
& \left(b_{i,j} \left(\delta_{i,t} - \delta_{j,t} \right) - P_{i,j}^{fmax} \right) \perp \rho_{i,j,t}^{fmin} && \forall i, j \in B(i), \forall t && (44) \\
& \left(P_{i,j}^{fmax} - b_{i,j} \left(\delta_{i,t} - \delta_{j,t} \right) \right) \perp \rho_{i,j,t}^{fmax} && \forall i, j \in B(i), \forall t && (45) \\
& P_t^{TS} \perp \rho_{i,t}^{pTSmin} && \forall i, j \in B(i), \forall t && (46) \\
& \left(P^{max,TS} - P_t^{TS} \right) \perp \rho_{i,t}^{bTMmax} && \forall i, j \in B(i), \forall t && (47) \\
& PL_{i,t} \perp \rho_{i,t}^{PLmin} && \forall i, j \in B(i), \forall t && (48)
\end{aligned}
$$

$$(L_{i,t} - PL_{i,t}) \perp \rho^{PLmax}_{i,t} \qquad \forall i, j \in B(i), \forall t \tag{49}$$

$$(35) - (39) \tag{50}$$

3 MPEC Formulation

Each microgrid operator solves its own bilevel problem in order to find its most beneficial decisions. The KKT conditions for each microgrid are shown in this section.

$$Cg_m - \lambda^{MG}_{m,t} - \beta^{gmin}_{m,t} + \beta^{gmax}_{m,t} = 0 \qquad \forall m, t \tag{51}$$

$$C^E_m - \lambda^{MG}_{m,t} - \beta^{pshmin}_{m,t} + \beta^{pshmax}_{m,t} = 0 \qquad \forall m, t \tag{52}$$

$$Cb_m - \lambda^{MG}_{m,t} \eta b_m - \beta^{pdmin}_{m,t} + \beta^{pdmax}_{m,t} = 0 \qquad \forall m, t \tag{53}$$

$$Cb_m + \lambda^{MG}_{m,t} / \eta b_m - \beta^{pcmin}_{m,t} + \beta^{pcmax}_{m,t} = 0 \qquad \forall m, t \tag{54}$$

$$\beta^{rct}_{m,t} - \beta^{rct}_{m,t+1} - \beta^{rmin}_{m,t} + \beta^{rmax}_{m,t} = 0 \qquad \forall m, t > 1 \tag{55}$$

$$\beta^{rct}_{m,t} + \beta^{rcmax}_{m,t} - \beta^{rmin}_{m,t} + \beta^{rmax}_{m,t} = 0 \qquad \forall m, t = T \tag{56}$$

$$- \lambda^{MG}_{m,t} - \beta^{prmin}_{m,t} + \beta^{prmax}_{m,t} = 0 \qquad \forall m, t \tag{57}$$

$$- P^{s,TM}_{m,t} - \beta^{o}_{m,t} + P^{s,TM}_{m,t} \beta^{str}_{m,t} + \beta^{oTM}_{m,m,t} = 0 \qquad \forall m, t \tag{58}$$

$$P^{b,TM}_{m,t} - \beta^{b}_{m,t} - P^{b,TM}_{m,t} \beta^{str}_{m,t} - \beta^{bTM}_{m,m,t} = 0 \qquad \forall m, t \tag{59}$$

$$\begin{aligned} & - o_{m,t} + \lambda^{MG}_{m,t} + \beta^{smax}_{m,t} + o_{m,t} \beta^{str}_{m,m,t} + \beta^{TM}_{m,m,t} \\ & - \beta^{sTMmin}_{m,m,t} + \beta^{sTMmax}_{m,m,t} = 0 \qquad \forall m, t \end{aligned} \tag{60}$$

$$o_{m,t} \beta^{str}_{m,t} + \beta^{TM}_{m,k,t} - \beta^{sTMmin}_{m,k,t} + \beta^{sTMmax}_{m,k,t} = 0 \qquad \forall m, k, k \neq m, \forall t \tag{61}$$

$$\begin{aligned} & b_{m,t} - \lambda^{MG}_{m,t} + \beta^{bmax}_{m,t} - b_{m,t} \beta^{str}_{m,m,t} - \beta^{TM}_{m,m,t} \\ & - \beta^{bTMmin}_{m,m,t} + \beta^{bTMmax}_{m,m,t} = 0 \qquad \forall m, t \end{aligned} \tag{62}$$

$$- b_{m,t} \beta^{str}_{m,t} - \beta^{TM}_{m,k,t} - \beta^{bTMmin}_{m,k,t} + \beta^{bTMmax}_{m,k,t} = 0 \qquad \forall m, k, k \neq m, \forall t \tag{63}$$

$$- 0.3 C^{TS}_t + \lambda^{MG}_{m,t} + \beta^{smax}_{m,t} - \beta^{sDMmin}_{m,t} + \beta^{sDMmax}_{m,t} = 0 \qquad \forall m, t \tag{64}$$

$$\sum_{\Theta^M_i} \left(\lambda^{DM}_{i,t} \right) - \lambda^{MG}_{m,t} + \beta^{bmax}_{m,t} - \beta^{bDMmin}_{m,t} + \beta^{bDMmax}_{m,t} = 0 \qquad \forall m, t \tag{65}$$

$$- \beta^{oTM}_{m,k,t} - \beta^{\gamma,smin}_{m,k,t} = 0 \qquad \forall m, k, t \tag{66}$$

$$\beta^{oTM}_{m,k,t} - \beta^{\gamma,smax}_{m,k,t} + P^{max,TM} \beta^{str}_{m,t} = 0 \qquad \forall m, k, t \tag{67}$$

$$- \beta^{bTM}_{m,k,t} - \beta^{\gamma,bmin}_{m,k,t} = 0 \qquad \forall m, k, t \tag{68}$$

$$\beta^{bTM}_{m,k,t} - \beta^{\gamma,bmax}_{m,k,t} + P^{max,TM} \beta^{str}_{m,t} = 0 \qquad \forall m, k, t \tag{69}$$

$$\sum_{m,k} \left(\beta^{bTM}_{m,k,t} - \beta^{oTM}_{m,k,t}\right) = 0 \qquad \forall t \quad (70)$$

$$o_{m,t} \perp \beta^{o}_{m,t} \qquad \forall m,t \quad (71)$$

$$b_{m,t} \perp \beta^{b}_{m,t} \qquad \forall m,t \quad (72)$$

$$Pg_{m,t} \perp \beta^{gmin}_{m,t} \qquad \forall m,t \quad (73)$$

$$\left(Pg^{max}_{m} - Pg_{m,t}\right) \perp \beta^{gmax}_{m,t} \qquad \forall m,t \quad (74)$$

$$Pr_{m,t} \perp \beta^{prmin}_{m,t} \qquad \forall m,t \quad (75)$$

$$\left(Gr_{m,t} - Pr_{m,t}\right) \perp \beta^{prmax}_{m,t} \qquad \forall m,t \quad (76)$$

$$\left(RC_{m,t} - SoC^{min} EB_{m}\right) \perp \beta^{rmin}_{m,t} \qquad \forall m,t \quad (77)$$

$$\left(SoC^{max} EB_{m} - RC_{m,t}\right) \perp \beta^{rmax}_{m,t} \qquad \forall m,t \quad (78)$$

$$Pd_{m,t} \perp \beta^{pdmin}_{m,t} \qquad \forall m,t \quad (79)$$

$$\left(PB_{m} - Pd_{m,t}\right) \perp \beta^{pdmax}_{m,t} \qquad \forall m,t \quad (80)$$

$$Pc_{m,t} \perp \beta^{pcmin}_{m,t} \qquad \forall m,t \quad (81)$$

$$\left(PB_{m} - Pc_{m,t}\right) \perp \beta^{cdmax}_{m,t} \qquad \forall m,t \quad (82)$$

$$P^{sh}_{m,t} \perp \beta^{shmin}_{m,t} \qquad \forall m,t \quad (83)$$

$$\left(D_{m,t} - P^{sh}_{m,t}\right) \perp \beta^{shmax}_{m,t} \qquad \forall m,t \quad (84)$$

$$\left(P^{max}_{m} - P^{b,DM}_{m,t} - P^{b,TM}_{m,t}\right) \perp \beta^{bmax}_{m,t} \qquad \forall m,t \quad (85)$$

$$\left(P^{max}_{m} - P^{s,DM}_{m,t} - P^{s,TM}_{m,t}\right) \perp \beta^{smax}_{m,t} \qquad \forall m,t \quad (86)$$

$$P^{b,DM}_{m,t} \perp \beta^{bDMmin}_{m,t} \qquad \forall m,t \quad (87)$$

$$\left(P^{max}_{m} - P^{b,DM}_{m,t}\right) \perp \beta^{bDMmax}_{m,t} \qquad \forall m,t \quad (88)$$

$$P^{s,DM}_{m,t} \perp \beta^{sDMmin}_{m,t} \qquad \forall m,t \quad (89)$$

$$\left(P^{max}_{m} - P^{s,DM}_{m,t}\right) \perp \beta^{sDMmax}_{m,t} \qquad \forall m,t \quad (90)$$

$$\gamma^{sTMmin}_{m,t} \perp \beta^{\gamma,smin}_{m,k,t} \qquad \forall m,k,t \quad (91)$$

$$\gamma^{sTMmax}_{m,t} \perp \beta^{\gamma,smax}_{m,k,t} \qquad \forall m,k,t \quad (92)$$

$$\gamma^{bTMmin}_{m,t} \perp \beta^{\gamma,bmin}_{m,k,t} \qquad \forall m,k,t \quad (93)$$

$$\gamma^{bTMmax}_{m,t} \perp \beta^{\gamma,bmax}_{m,k,t}) \qquad \forall m,k,t \quad (94)$$

$$P^{s,TM}_{m,t} \perp \beta^{sTMmin}_{m,k,t} \qquad \forall m,k,t \quad (95)$$

$$\left(P^{max,TM} - P^{s,TM}_{m,t}\right) \perp \beta^{sTMmax}_{m,k,t} \qquad \forall m,k,t \quad (96)$$

$$P_{m,t}^{b,TM} \perp \beta_{m,k,t}^{bTMmin} \qquad \forall m,k,t \quad (97)$$

$$\left(P^{max,TM} - P_{m,t}^{b,TM}\right) \perp \beta_{m,k,t}^{bTMmax} \qquad \forall m,k,t \quad (98)$$

$$(2) - (19), (21) - (23), (25) - (33), (35) - (49) \qquad (99)$$

The joint solution of each microgrid operator MPEC constitute the EPEC. Linearization techniques of the complementarity conditions that are found in this problem could be found in the following reference:

A. J. Conejo, L. Baringo, S. J. Kazempour, A. S. Siddiqui, "Investment in Electricity Generation and Transmission. Decision Making under Uncertainty" Springer: New York, New York, 2016.