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$\theta p(\Lambda, p)$-OPEN FUNCTIONS AND $\theta p(\Lambda, p)$-CLOSED FUNCTIONS

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Abstract. This article deals with the concepts of $\theta p(\Lambda, p)$-open functions and $\theta p(\Lambda, p)$-closed functions. Moreover, several characterizations of $\theta p(\Lambda, p)$-open functions and $\theta p(\Lambda, p)$-closed functions are considered.

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1. Introduction

The concept of weakly open functions was first introduced by Rose [12]. Rose and Janković [11] investigated some of the fundamental properties of weakly closed functions. Caldas and Navalagi [5] introduced two new classes of functions called weakly preopen functions and weakly preclosed functions as generalization of weak openness and weak closedness due to [12] and [11], respectively. Moreover, Caldas and Navalagi [4] introduced and investigated the concepts of weakly semi-open functions and weakly semi-closed functions as a new generalization of weakly open functions and weakly closed functions, respectively. Noiri and Popa [8] studied a new class of functions called M-closed functions as functions defined between sets satisfying some conditions. Pal et al. [10] introduced and studied the notion of pre-θ-closed sets in topological spaces. Caldas et al. [3] introduced the notions of pre-θ-derided, pre-θ-border, pre-θ-frontier and pre-θ-exterior of a set. Noiri [9] introduced and investigated the notion of θ-precontinuous functions. Furthermore, Caldas et al. [3] defined the concepts of θ-preopenness and θ-preclosedness as a natural dual to the θ-precontinuity due to Noiri [9]. In [2], the present authors investigated some properties of (Λ, sp)-closed sets and (Λ, sp)-open sets. Boonpok and Viriyapong [1] introduced and studied the notions of (Λ, p)-closed sets and (Λ, p)-open sets. Srisarakham and Boonpok [13] investigated several properties of $\delta p(\Lambda, s)$-closed sets and the

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$\delta p(\Lambda, s)$-closure operator. In this article, we introduce the concepts of $\theta(\Lambda, p)$-open functions and $\theta(\Lambda, p)$-closed functions. Moreover, several characterizations of $\theta(\Lambda, p)$-open functions and $\theta(\Lambda, p)$-closed functions are investigated.

2. Preliminaries

Throughout the present paper, spaces (X, τ) and (Y, σ) (or simply X and Y) always mean topological spaces on which no separation axioms are assumed unless explicitly stated. For a subset A of a topological space (X, τ), Cl(A) and Int(A), represent the closure and the interior of A, respectively. A subset A of a topological space (X, τ) is said to be *preopen* [7] if $A \subseteq \text{Int}(\text{Cl}(A))$. The complement of a preopen set is called *preclosed*. The family of all preopen sets of a topological space (X, τ) is denoted by $PO(X, \tau)$. A subset $\Lambda_p(A)$ [6] is defined as follows: $\Lambda_p(A) = \cap\{U \mid A \subseteq U, U \in PO(X, \tau)\}$. A subset A of a topological space (X, τ) is called a Λ_p-*set* [1] (*pre*-Λ-*set* [6]) if $A = \Lambda_p(A)$. A subset A of a topological space (X, τ) is called (Λ, p)-*closed* [1] if $A = T \cap C$, where T is a Λ_p-set and C is a preclosed set. The complement of a (Λ, p)-closed set is called (Λ, p)-*open*. The family of all (Λ, p)-open (resp. (Λ, p)-closed) sets in a topological space (X, τ) is denoted by $\Lambda_pO(X, \tau)$ (resp. $\Lambda_pC(X, \tau)$). Let A be a subset of a topological space (X, τ). A point $x \in X$ is called a (Λ, p)-*cluster point* [1] of A if $A \cap U \neq \emptyset$ for every (Λ, p)-open set U of X containing x. The set of all (Λ, p)-cluster points of A is called the (Λ, p)-*closure* [1] of A and is denoted by $A^{(\Lambda,p)}$. The union of all (Λ, p)-open sets of X contained in A is called the (Λ, p)-*interior* [1] of A and is denoted by $A_{(\Lambda,p)}$.

The $\theta(\Lambda, p)$-*closure* [1] of A, $A^{\theta(\Lambda,p)}$, is defined as follows:
$A^{\theta(\Lambda,p)} = \{x \in X \mid A \cap U^{(\Lambda,p)} \neq \emptyset$ for each (Λ, p)-open set U containing $x\}$. A subset A of a topological space (X, τ) is called $\theta(\Lambda, p)$-*closed* [1] if $A = A^{\theta(\Lambda,p)}$. The complement of a $\theta(\Lambda, p)$-closed set is said to be $\theta(\Lambda, p)$-*open*. A point $x \in X$ is called a $\theta(\Lambda, p)$-*interior point* [14] of A if $x \in U \subseteq U^{(\Lambda,p)} \subseteq A$ for some $U \in \Lambda_pO(X, \tau)$. The set of all $\theta(\Lambda, p)$-interior points of A is called the $\theta(\Lambda, p)$-*interior* [14] of A and is denoted by $A_{\theta(\Lambda,p)}$.

Lemma 1. [14] *For subsets A and B of a topological space (X, τ), the following properties hold:*

(1) $X - A^{\theta(\Lambda,p)} = [X - A]_{\theta(\Lambda,p)}$ *and* $X - A_{\theta(\Lambda,p)} = [X - A]^{\theta(\Lambda,p)}$.
(2) *A is $\theta(\Lambda, p)$-open if and only if $A = A_{\theta(\Lambda,p)}$.*
(3) $A \subseteq A^{(\Lambda,p)} \subseteq A^{\theta(\Lambda,p)}$ *and* $A_{\theta(\Lambda,p)} \subseteq A_{(\Lambda,p)} \subseteq A$.
(4) *If $A \subseteq B$, then $A^{\theta(\Lambda,p)} \subseteq B^{\theta(\Lambda,p)}$ and $A_{\theta(\Lambda,p)} \subseteq B_{\theta(\Lambda,p)}$.*
(5) *If A is (Λ, p)-open, then $A^{(\Lambda,p)} = A^{\theta(\Lambda,p)}$.*

A subset A of a topological space (X, τ) is said to be $p(\Lambda, p)$-*open* [1] (resp. $\alpha(\Lambda, p)$-*open* [15], $r(\Lambda, p)$-*open* [1]) if $A \subseteq [A^{(\Lambda,p)}]_{(\Lambda,p)}$ (resp. $A \subseteq [[A_{(\Lambda,p)}]^{(\Lambda,p)}]_{(\Lambda,p)}$, $A = [A^{(\Lambda,p)}]_{(\Lambda,p)}$). The complement of a

$p(\Lambda,p)$-open (resp. $\alpha(\Lambda,p)$-open, $r(\Lambda,p)$-open) set is called $p(\Lambda,p)$-*closed* (resp. $\alpha(\Lambda,p)$-*closed*, $r(\Lambda,p)$-*closed*). The intersection of all $p(\Lambda,p)$-closed sets of X containing A is called the $p(\Lambda,p)$-*closure* of A and is denoted by $A^{p(\Lambda,p)}$. Let A be a subset of a topological space (X,τ). A point $x\in X$ is called a $\theta p(\Lambda,p)$-*cluster point* of A if $A\cap U^{p(\Lambda,p)}\neq\emptyset$ for every $p(\Lambda,p)$-open set U of X containing x. The set of all $\theta p(\Lambda,p)$-cluster points of A is called the $\theta p(\Lambda,p)$-*closure* of A and is denoted by $A^{\theta p(\Lambda,p)}$. If $A=A^{\theta p(\Lambda,p)}$, then A is called $\theta p(\Lambda,p)$-*closed*. The complement of a $\theta p(\Lambda,p)$-closed set is called $\theta p(\Lambda,p)$-*open*. The $\theta p(\Lambda,p)$-*interior* of A is defined by the union of all $\theta p(\Lambda,p)$-open sets of X contained in A and is denoted by $A_{\theta p(\Lambda,p)}$.

Lemma 2. *For subsets A and B of a topological space (X,τ), the following properties hold:*

(1) $X-A^{\theta p(\Lambda,p)}=[X-A]_{\theta p(\Lambda,p)}$ *and* $X-A_{\theta p(\Lambda,p)}=[X-A]^{\theta p(\Lambda,p)}$.
(2) *A is $\theta p(\Lambda,p)$-open if and only if* $A=A_{\theta p(\Lambda,p)}$.
(3) $A\subseteq A^{p(\Lambda,p)}\subseteq A^{\theta p(\Lambda,p)}$ *and* $A_{\theta p(\Lambda,p)}\subseteq A_{p(\Lambda,p)}\subseteq A$.
(4) *If $A\subseteq B$, then* $A^{\theta p(\Lambda,p)}\subseteq B^{\theta p(\Lambda,p)}$ *and* $A_{\theta p(\Lambda,p)}\subseteq B_{\theta p(\Lambda,p)}$.
(5) *If A is $p(\Lambda,p)$-open, then* $A^{p(\Lambda,p)}=A^{\theta p(\Lambda,p)}$.

3. Characterizations of $\theta p(\Lambda,p)$-open functions

In this section, we introduce the concept of $\theta p(\Lambda,p)$-open functions. Moreover, some characterizations of $\theta p(\Lambda,p)$-open functions are discussed.

Definition 1. *A functions $f:(X,\tau)\to(Y,\sigma)$ is said to be $\theta p(\Lambda,p)$-open if $f(U)\subseteq[f(U^{(\Lambda,p)})]_{\theta p(\Lambda,p)}$ for each (Λ,p)-open set U of X.*

Theorem 1. *For a function $f:(X,\tau)\to(Y,\sigma)$, the following properties are equivalent:*

(1) *f is $\theta p(\Lambda,p)$-open;*
(2) $f(A_{\theta(\Lambda,p)})\subseteq[f(A)]_{\theta p(\Lambda,p)}$ *for every subset A of X;*
(3) $[f^{-1}(B)]_{\theta(\Lambda,p)}\subseteq f^{-1}(B_{\theta p(\Lambda,p)})$ *for every subset B of Y;*
(4) $f^{-1}(B^{\theta p(\Lambda,p)})\subseteq[f^{-1}(B)]^{\theta(\Lambda,p)}$ *for every subset B of Y;*
(5) $f(K_{(\Lambda,p)})\subseteq[f(K)]_{\theta p(\Lambda,p)}$ *for each (Λ,p)-closed set K of X;*
(6) $f([U^{(\Lambda,p)}]_{(\Lambda,p)})\subseteq[f(U^{(\Lambda,p)})]_{\theta p(\Lambda,p)}$ *for each (Λ,p)-open set U of X;*
(7) $f(U)\subseteq[f(U^{(\Lambda,p)})]_{\theta p(\Lambda,p)}$ *for each $r(\Lambda,p)$-open set U of X;*
(8) $f(U)\subseteq[f(U^{(\Lambda,p)})]_{\theta p(\Lambda,p)}$ *for each $\alpha(\Lambda,p)$-open set U of X.*

Proof. The proofs of (5) $\Rightarrow$ (6) $\Rightarrow$ (7) $\Rightarrow$ (8) $\Rightarrow$ (1) are straightforward and are omitted.

(1) $\Rightarrow$ (2): Let A be any subset of X and $x\in A_{\theta(\Lambda,p)}$. Then, there exists a (Λ,p)-open set U of X such that

$$x\in U\subseteq U^{(\Lambda,p)}\subseteq U.$$

Then, $f(x) \in f(U) \subseteq f(U^{(\Lambda,p)}) \subseteq f(A)$. Since f is $\theta p(\Lambda,p)$-open, $f(U) \subseteq [f(U^{(\Lambda,p)})]_{\theta p(\Lambda,p)} \subseteq [f(A)]_{\theta p(\Lambda,p)}$. It implies that

$$f(x) \in [f(A)]_{\theta p(\Lambda,p)}.$$

Therefore, $x \in f^{-1}([f(A)]_{\theta p(\Lambda,p)})$. Thus, $A_{\theta(\Lambda,p)} \subseteq f^{-1}([f(A)]_{\theta p(\Lambda,p)})$ and hence $f(A_{\theta(\Lambda,p)}) \subseteq [f(A)]_{\theta p(\Lambda,p)}$.

(2) $\Rightarrow$ (3): Let B be any subset of Y. Then by (2),

$$f([f^{-1}(B)]_{\theta(\Lambda,p)}) \subseteq B_{\theta p(\Lambda,p)}.$$

Thus, $[f^{-1}(B)]_{\theta(\Lambda,p)} \subseteq f^{-1}(B_{\theta p(\Lambda,p)})$.

(3) $\Rightarrow$ (4): Let B be any subset of Y. Using (3), we have

$$\begin{aligned} X - [f^{-1}(B)]^{\theta(\Lambda,p)} &= [X - f^{-1}(B)]_{\theta(\Lambda,p)} \\ &= [f^{-1}(Y - B)]_{\theta(\Lambda,p)} \\ &\subseteq f^{-1}([Y - B]_{\theta p(\Lambda,p)}) \\ &= f^{-1}(Y - B^{\theta p(\Lambda,p)}) \\ &= X - f^{-1}(B^{\theta p(\Lambda,p)}) \end{aligned}$$

and hence $f^{-1}(B^{\theta p(\Lambda,p)}) \subseteq [f^{-1}(B)]^{\theta(\Lambda,p)}$.

(4) $\Rightarrow$ (5): Let K be any (Λ,p)-closed set of X. Thus, by (4),

$$f^{-1}([Y - f(K)]^{\theta p(\Lambda,p)}) \subseteq [f^{-1}(Y - f(K))]^{\theta(\Lambda,p)}.$$

We have

$$\begin{aligned} f^{-1}([Y - f(K)]^{\theta p(\Lambda,p)}) &= f^{-1}(Y - [f(K)]_{\theta p(\Lambda,p)}) \\ &= X - f^{-1}([f(K)]_{\theta p(\Lambda,p)}). \end{aligned}$$

On the other hand,

$$\begin{aligned} [f^{-1}(Y - f(K))]^{\theta(\Lambda,p)} &= [X - f^{-1}(f(K))]^{\theta(\Lambda,p)} \\ &\subseteq [X - K]^{\theta(\Lambda,p)} \\ &= X - K_{\theta(\Lambda,p)} \\ &= X - K_{(\Lambda,p)}, \end{aligned}$$

since K is (Λ,p)-closed. Thus, $K_{(\Lambda,p)} \subseteq f^{-1}([f(K)]_{\theta p(\Lambda,p)})$ and hence $f(K_{(\Lambda,p)}) \subseteq [f(K)]_{\theta p(\Lambda,p)}$. □

Theorem 2. *Let $f : (X,\tau) \to (Y,\sigma)$ be a bijective function. Then, the following properties are equivalent:*

(1) *f is $\theta p(\Lambda,p)$-open;*

(2) $[f(U)]^{\theta p(\Lambda,p)} \subseteq f(U^{(\Lambda,p)})$ *for every (Λ,p)-open set U of X;*

(3) $[f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(K)$ *for every (Λ,p)-closed set K of X.*

Proof. (1) $\Rightarrow$ (3): Let K be any (Λ,p)-closed set of X. Then, we have

$$\begin{aligned} Y - f(K) &= f(X-K) \\ &\subseteq [f([X-K]^{(\Lambda,p)})]_{\theta p(\Lambda,p)} \end{aligned}$$

and hence $Y - f(K) \subseteq Y - [f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)}$. Thus,

$$[f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(K).$$

(3) $\Rightarrow$ (2): Let U be any (Λ,p)-open set of X. Since $U^{(\Lambda,p)}$ is (Λ,p)-closed and $U \subseteq [U^{(\Lambda,p)}]_{(\Lambda,p)}$, by (3) we have

$$\begin{aligned} [f(U)]^{\theta p(\Lambda,p)} &\subseteq [f([U^{(\Lambda,p)}]_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \\ &\subseteq f(U^{(\Lambda,p)}). \end{aligned}$$

(2) $\Rightarrow$ (1): Let U be any (Λ,p)-open set of X. By (2), we have

$$[f(X-U^{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f([X-U^{(\Lambda,p)}]^{(\Lambda,p)}).$$

Since f is bijective, $[f(X-U^{(\Lambda,p)})]^{\theta p(\Lambda,p)} = Y - [f(U^{(\Lambda,p)})]_{\theta p(\Lambda,p)}$ and

$$\begin{aligned} f([X-U^{(\Lambda,p)}]^{(\Lambda,p)}) &= f(X-[U^{(\Lambda,p)}]_{(\Lambda,p)}) \\ &\subseteq f(X-U) \\ &= Y - f(U). \end{aligned}$$

Thus, $f(U) \subseteq [f(U^{(\Lambda,p)})]_{\theta p(\Lambda,p)}$ and hence f is $\theta p(\Lambda,p)$-open. □

4. Characterizations of $\theta p(\Lambda,p)$-closed functions

In this section, we introduce the notion of $\theta p(\Lambda,p)$-closed functions. Furthermore, several characterizations of $\theta p(\Lambda,p)$-closed functions are considered.

Definition 2. *A functions $f:(X,\tau)\to(Y,\sigma)$ is said to be $\theta p(\Lambda,p)$-closed if $[f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(K)$ for each (Λ,p)-closed set K of X.*

Theorem 3. *For a function $f:(X,\tau)\to(Y,\sigma)$, the following properties are equivalent:*

(1) *f is $\theta p(\Lambda,p)$-closed;*

(2) $[f(U)]^{\theta p(\Lambda,p)} \subseteq f(U^{(\Lambda,p)})$ *for every (Λ,p)-open set U of X;*

(3) $[f(U)]^{\theta p(\Lambda,p)} \subseteq f(U^{(\Lambda,p)})$ *for every $p(\Lambda,p)$-open set U of X;*

(4) $[f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(K)$ *for every* $p(\Lambda,p)$*-closed set* K *of* X*;*

(5) $[f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(K)$ *for every* $\alpha(\Lambda,p)$*-closed set* K *of* X*;*

(6) $[f([A^{(\Lambda,p)}]_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(A^{(\Lambda,p)})$ *for every subset* A *of* X*.*

Proof. $(1) \Rightarrow (2)$: Let U be any (Λ,p)-open set of X. Then by (1),

$$[f(U)]^{\theta p(\Lambda,p)} = [f(U_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq [f([U^{(\Lambda,p)}]_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(U^{(\Lambda,p)}).$$

$(2) \Rightarrow (3)$: Let U be any $p(\Lambda,p)$-open set of X. Using (2), we have

$$[f(U)]^{\theta p(\Lambda,p)} \subseteq [f([U^{(\Lambda,p)}]_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f([[U^{(\Lambda,p)}]_{(\Lambda,p)}]^{(\Lambda,p)}) \subseteq f(U^{(\Lambda,p)}).$$

$(3) \Rightarrow (4)$: Let K be any $p(\Lambda,p)$-closed set of X. Then, we have

$$[f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f([K_{(\Lambda,p)}]^{(\Lambda,p)}) \subseteq f(K).$$

It is clear that $(4) \Rightarrow (5) \Rightarrow (6) \Rightarrow (1)$. □

Definition 3. [1] *A topological space* (X,τ) *is said to be* Λ_p*-regular if for each* (Λ,p)*-closed set* F *and each* $x \notin F$*, there exist disjoint* (Λ,p)*-open sets* U *and* V *such that* $x \in U$ *and* $F \subseteq V$*.*

Lemma 3. [1] *A topological space* (X,τ) *is* Λ_p*-regular if and only if for each* $x \in X$ *and each* (Λ,p)*-open set* U *containing* x*, there exists a* (Λ,p)*-open set* V *such that* $x \in V \subseteq V^{(\Lambda,p)} \subseteq U$*.*

Theorem 4. *Let* (Y,σ) *be a* Λ_p*-regular space. Then, for a function* $f : (X,\tau) \to (Y,\sigma)$*, the following properties are equivalent:*

(1) f *is* $\theta p(\Lambda,p)$*-closed;*

(2) $[f(U)]^{\theta p(\Lambda,p)} \subseteq f(U^{(\Lambda,p)})$ *for each* $r(\Lambda,p)$*-open set* U *of* X*;*

(3) *for each subset* B *of* Y *and each* (Λ,p)*-open set* U *of* X *with* $f^{-1}(B) \subseteq U$*, there exists a* $\theta p(\Lambda,p)$*-open set* V *of* Y *such that* $B \subseteq V$ *and* $f^{-1}(V) \subseteq U^{(\Lambda,p)}$*;*

(4) *for each point* $y \in Y$ *and each* (Λ,p)*-open set* U *of* X *with* $f^{-1}(y) \subseteq U$*, there exists a* $\theta p(\Lambda,p)$*-open set* V *of* Y *containing* y *and* $f^{-1}(V) \subseteq U^{(\Lambda,p)}$*.*

Proof. $(1) \Rightarrow (2)$ and $(3) \Rightarrow (4)$: The proofs are obvious.

$(2) \Rightarrow (3)$: Let B be any subset of Y and U be any (Λ,p)-open set of X with $f^{-1}(B) \subseteq U$. Then, $f^{-1}(B) \cap [X - U^{(\Lambda,p)}]^{(\Lambda,p)} = \emptyset$ and hence $B \cap f([X - U^{(\Lambda,p)}]^{(\Lambda,p)}) = \emptyset$. Since $X - U^{(\Lambda,p)}$ is $r(\Lambda,p)$-open, $B \cap [f(X - U^{(\Lambda,p)})]^{\theta p(\Lambda,p)} = \emptyset$ by (2). Put $V = Y - [f(X - U^{(\Lambda,p)})]^{\theta p(\Lambda,p)}$. Then, V is a $\theta p(\Lambda,p)$-open set of Y such that $B \subseteq V$ and

$$\begin{aligned} f^{-1}(V) &\subseteq X - f^{-1}([f(X - U^{(\Lambda,p)})]^{\theta p(\Lambda,p)}) \\ &\subseteq X - f^{-1}(f(X - U^{(\Lambda,p)})) \\ &\subseteq U^{(\Lambda,p)}. \end{aligned}$$

$(4) \Rightarrow (1)$: Let K be any (Λ, p)-closed set of Y and $y \in Y - f(K)$. Since $f^{-1}(y) \subseteq X - K$, there exists a $\theta p(\Lambda, p)$-open set V of Y such that $y \in V$ and $f^{-1}(V) \subseteq [X - K]^{(\Lambda,p)} = X - K_{(\Lambda,p)}$ by (4). Thus, $V \cap f(K_{(\Lambda,p)}) = \emptyset$ and hence $y \in Y - [f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)}$. It implies that $[f(K_{(\Lambda,p)})]^{\theta p(\Lambda,p)} \subseteq f(K)$. This shows that f is $\theta p(\Lambda, p)$-closed. □

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